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MATERIALS PARAMETERS THAT GOVERN THE RAIN EROSION BEHAVIOR OF POLYMERIC COATINGS AND COMPOSITES AT SUBSONIC VELOCITIES

GEORGE F. SCHMITT, JR.

TECHNICAL REPORT AFML-TR-71-197

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AFML-TR-71-197

MATERIALS PARAMETERS THAT GOVERN THE RAIN EROSION BEHAVIOR OF POLYMERIC COATINGS AND COMPOSITES AT SUBSONIC VELOCITIES

GEORGE F. SCHMITT, JR.

FOREWORD

This report was prepared by the Elastomers and Coatings Branch, Nonmetallic Materials Division, Air Force Materials Laboratory, and was initiated under Project No. 7340, "Nonmetallic and Composite Materials," Task No. 734007, "Coatings for Energy Utilization, Control and Protective Functions" with George F. Schmitt, Jr. Acting as project engineer.

This report covers work performed from August 1968 to October 1970 and was released for publication in March 1971.

The author gratefully acknowledges the assistance of Messrs. C. J. Hurley, R. L. Vissoc, G. A. Clinehens, and T. Courney in the operation of the apparatus and the weight loss measurements.

This technical report has been reviewed and is approved.

WARREN P. JOHNSON, Chief
Elastomers and Coatings Branch
Nonmetallic Materials Division

ABSTRACT

Subsonic investigations of polymeric coatings, bulk polymers, and fiber reinforced polymeric composites are described for their erosion behavior and the influence of materials variables on their erosion response.

Polymeric coatings such as epoxies, polyesters, and amide-imides are brittle relative to the impinging water droplets with rupture of the film occurring very rapidly. The most resistant coatings such as elastomeric polyurethanes typically show no surface erosion at all but fail at isolated points associated with a breakdown of the composite (i.e., glass-epoxy) underneath the coating. Other elastomeric coatings such as neoprene will gradually erode on the surface by structural failure or tearing within the film; erosion of the composite then follows. The elastomeric coatings protect the surface by pulse attenuation of the impact load and by protecting the composite from the radial outflow of the impinging drop. The modulus of these coatings is related to their performance in a rain environment since it governs the stress level which is transmitted to the substrate.

The void content and type of reinforcement are shown to significantly influence the behavior of fiber reinforced composite structures in a subsonic rain erosion environment whether uncoated or coated. The effects of various fiber lay-up schemes with a particular fiber reinforcement have been found to be minor compared to void content effects.

ABSTRACT (CONT'D)

The addition of reinforcement to thermoplastic resin matrices increases the erosion rates of these materials by breakage of fibers and resulting loss of material. In thermosetting resins, the addition of reinforcement reduces the erosion rate of a bulk material by limiting the chunking and breakout of large pieces.

ILLUSTRATIONS

ILLUSTRATIONS (CONT'D)

TABLES

SECTION I

INTRODUCTION

Operation of aircraft in rainy environments has resulted in rain erosion on various components of these systems. Rain erosion has been a particular problem on radomes and other exterior plastic parts of aircraft because these components are nonmetallic (to be compatible with the radar), made of fiber-reinforced constructions (prone to erosion damage), and are typically located on the aircraft in positions which are subject to rain exposure. These problems have been primarily subsonic in nature because current aircraft do not operate supersonically, if at all possible, in actual rain.

Erosion protection of dielectric composites such as glass-reinforced plastics must be transparent for the purpose of radar transmission and hence, nonmetallic coatings, particularly elastomerics, have been used for this purpose. For structural composites such as graphite or boron fiber-reinforced constructions the radar transmission constraint does not apply; therefore, metallic coatings including the electroplated nickel have been used to provide excellent protection for these areas.

In a continuing research effort to explore candidate coatings materials and substrate construction, the Elastomers and Coatings Branch, Nonmetallic Materials Division of the Air Force Materials Laboratory has previously investigated a variety of advanced and currently available materials in a rotating arm apparatus (Reference 1). In these investigations an advanced rain erosion research apparatus has been used and this report describes some of the results found to date.

This report attempts to identify the important materials parameters which control the erosicn behavior of polymeric coatings and composites rather than providing just an evaluation or a relative ranking of the various materials.

SECTION II

APPARATUS DESCRIPTION

Subsonic and low supersonic rain erosion investigations are conducted by the Air Force Materials Laboratory on a rotating arm apparatus (See Figure 1). This equipment includes an 8-foot diameter propeller blade made of 4340 steel mounted horizontally and powered by a 400-horsepower electric motor. It is capable of attaining variable speeds up to 900 mph at the blade tip where the specimens are inserted. A detailed description may be found in Reference 2.

The speed of the equipment is regulated by a thyristor power supply from which rigid control is possible. A revolution counter is utilized for monitoring velocity; vibration pickups are used for gauging specimen balance and smoothness of operation. The rotating specimens are observed using a closed circuit television camera and a stroboscopic unit synchronized with the blade revolution. This system enables the observer to note the exact moment of coating failure which is penetration to the substrate or the loss of adhesion.

Mounted above the blade is the water system used to simulate the rain environment. The 8-foot diameter, 1 inch aluminum pipe ring is equipped with 96 equally spaced hypodermic needles to yield a rainfall simulation of 1 inch per hour. The hypodermic needles are No. 27 gauge which produces rain droplets of 1.5 to 2.0 mm diameter as determined photographically. The water system operated with low pressure in the spray ring enables a stream of undistorted water drops to impinge on the material specimens.

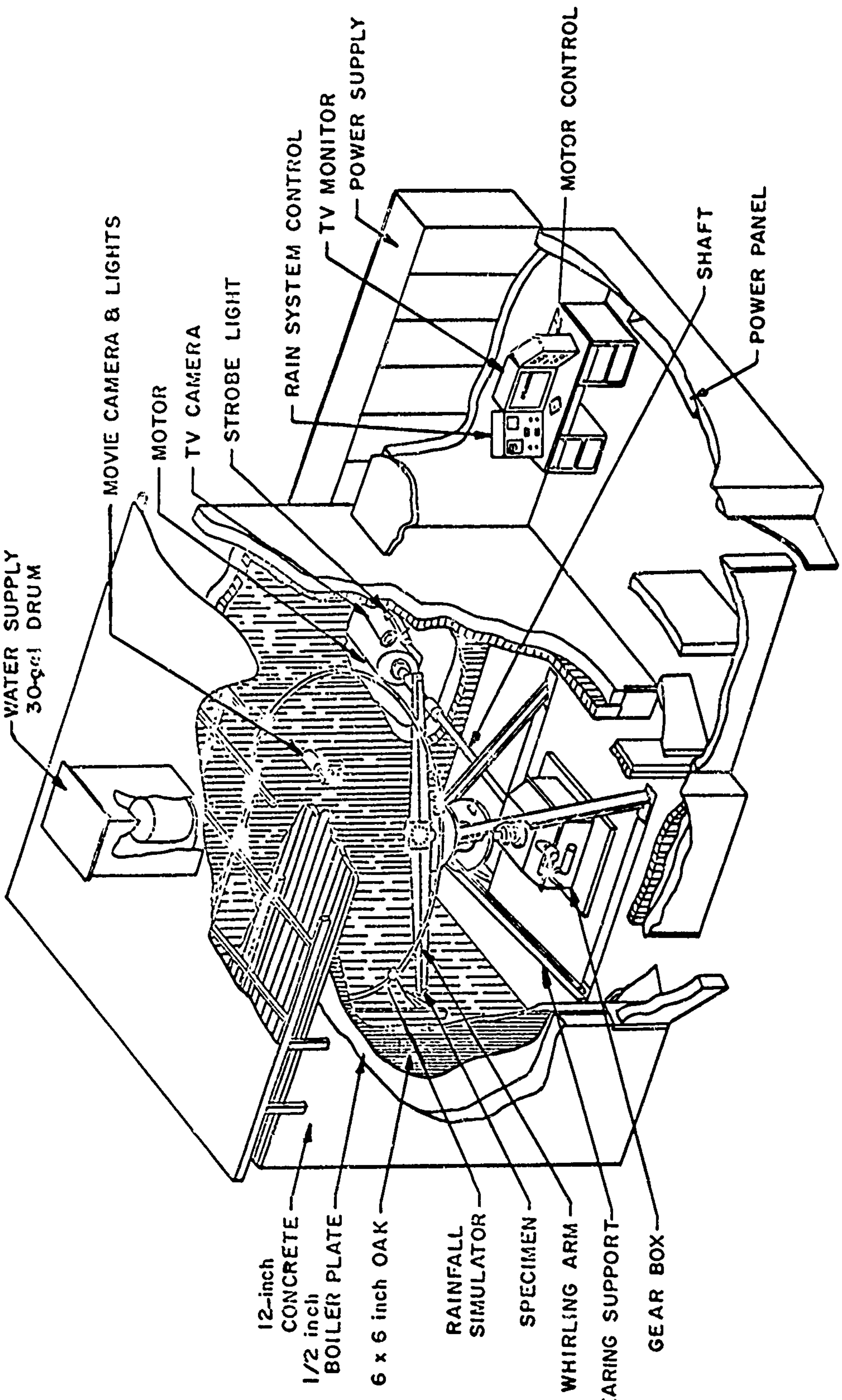
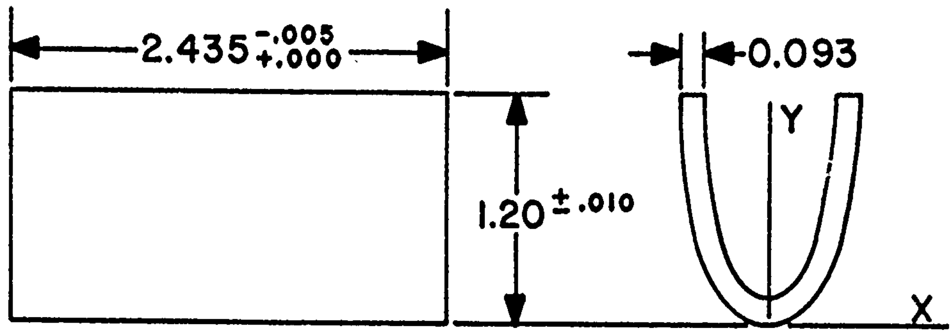


Figure 1. AFML Rotating Arm Apparatus

The specimen configurations are airfoil specimens of aluminum or various laminated materials with and without coatings (See Figure 2). These conformal specimens are employed extensively because they are easy to coat and their low drag and light weight allow the apparatus to be operated efficiently.

This rotating arm apparatus represented the first operational supersonic capability in the United States when it became operational in August 1968.

Various materials were evaluated under actual flight conditions in rain utilizing an F-100 F aircraft. These tests verified that the rankings and modes of failure obtained on the rotating arm are borne out in actual flight experience (References 2 and 3).



.0025 AIRFOIL - 4 INCH CHORD

DISTANCE FROM LEADING EDGE

% CHORD	ORDINATE (Y)	ABSCISSA (X)
.00	.00	.000
1.25	.05	.112
2.50	.10	.172
5.00	.20	.250
7.50	.30	.304
10.00	.40	.344
15.00	.60	.400
20.00	.80	.432
25.00	1.00	.439
30.00	1.20	.454

OUTER DIMENSIONS OF 0.093 INCH SPECIMEN
MATERIAL - GLASS EPOXY LAMINATE

Figure 2. Airfoil Type Used On Mach 1.2 Rain Erosion Test Apparatus, Wright-Patterson AFB, Ohio

SECTION III

EROSION BEHAVIOR OF POLYMERIC COATINGS

A wide variety of polymeric coatings have been investigated at 500 and 600 mph. A summary of these investigations on the rotating arm is shown in Table I and all of the data are listed in Appendix II. The times to failure are those times in the simulated environment at velocity required for penetration of the coating to the substrate or the loss of adhesion. Times for failure of the elastomeric coatings were approximately two thirds as long at 600 mph as those at 500 mph for thicknesses up to 40 mils, regardless of elastomer type or whether it was a sprayed coating or premolded, adhesively bonded boot. This reduction in time to failure is the result of greater impact pressures associated with the increased velocity damaging the coatings and the increased frequency of impingement with droplets since the simulated rain environment remained the same. Which of the two effects is most important at subsonic velocities is uncertain because the two effects are coupled in the rotating arm. However, the frequency of impact is probably more important since elastomeric materials are sensitive to multiple impingement effects but their ability to recover or partially recover between impacts gives them their superior erosion resistance compared to other polymeric (rigid) coatings.

The penetration phenomena by which coatings fail in a subsonic rain environment vary for different types of coatings. Epoxy, acrylic, silicone or polyester coatings possess essentially no erosion resistance and fail by brittle rupture of the coating (See Figure 3). Neoprene coatings gradually wear away with a true erosion phenomenon on the

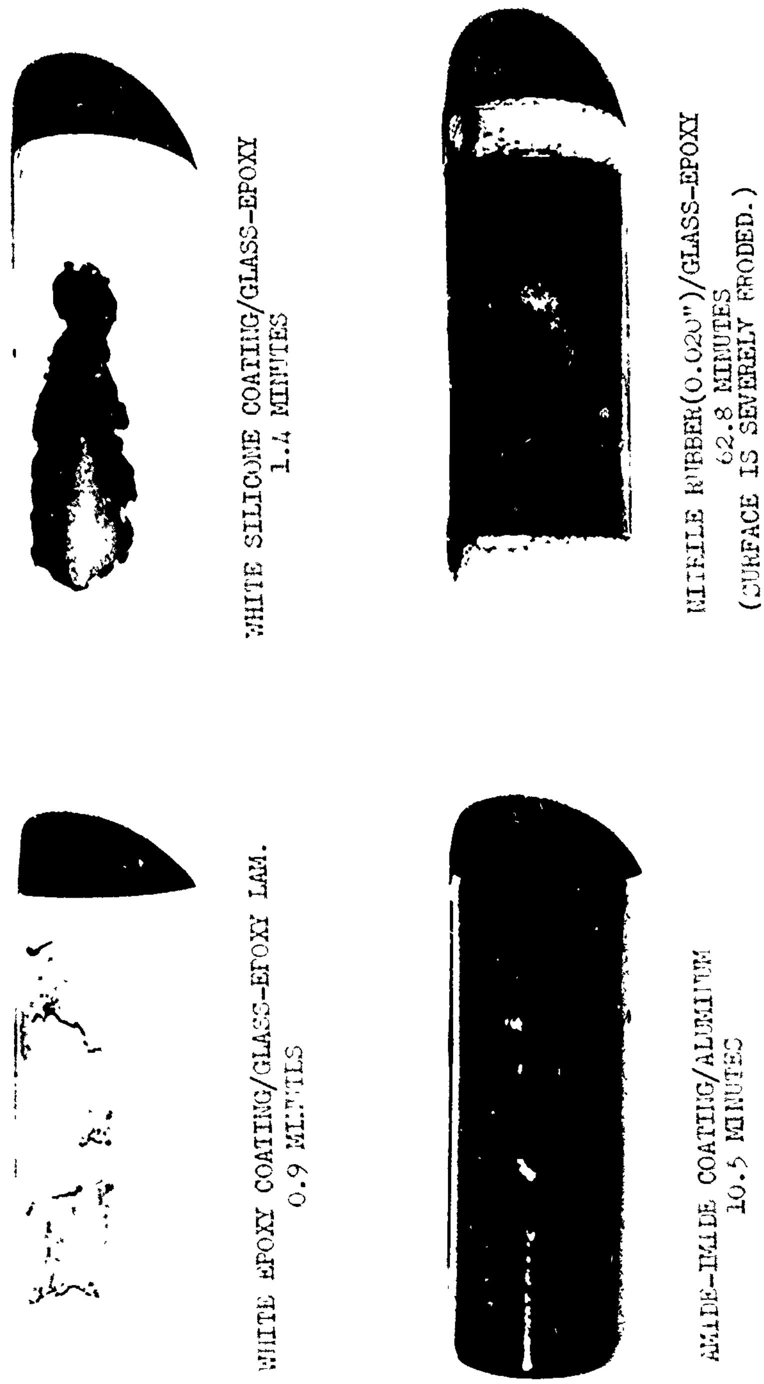


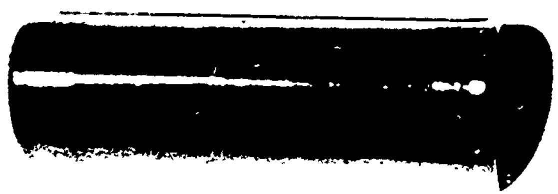
Figure 3. Polymeric-Coated Specimens, 500 MPH, 1 Inch/Hour Rainfall

surface or fail by a tearing of the film after adhesion loss with subsequent penetration. Polyurethanes do not erode on the surface but suffer point failures at weak spots in the substrate under the coating or at defects in the coating itself (See Figure 4). This has been noted for coated glass-epoxy laminates where under long exposure times (up to 180 minutes), the failure is the result of eventual breakdown of the laminate by repeated water droplet impacts. These conditions are compounded on advanced composities — particularly graphite-fiber reinforced — because of powdering of the substrate which occurs. A comparison of the polyurethane and neoprene coatings on glass-epoxy composite substrates is shown in Figure 5.

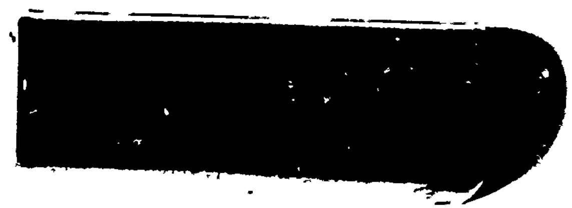
The behavior of elastomeric-coated composite structures has been analyzed by Morris (Reference 4). Common elastomeric coatings such as polyurethane and neoprene have a shock impedance lying for all loads between that of water and that of the substrate protected. Let a water droplet impact such a presumed thin coating. Equations for the pressure generated in the materials can be obtained from momentum and Hugoniot relations and solved graphically for the normal stress (σ_f) and particle velocity (u_f) behind the compressive wave initially propagated into the elastomer when the pressure pulse strikes the substrate. Shocks will be transmitted into the substrate and reflected into the coating.

SPRAYED NEOPRENE(0.012")/GLASS-EPOXY
20.0 MINUTES
(NOTE LOOSENING FROM SUBSTRATE)

SPRAYED NEOPRENE(0.012")/GLASS-EPOXY
40.0 MINUTES



SPRAYED POLYURETHANE(0.012")/GLASS-EPOXY
116MINUTES
(NO FAILURE)



SPRAYED POLYURETHANE(0.012")/GLASS-EPOXY
150.0 MINUTES
(NOTE ONE SMALL HOLE)

Figure 4. Elastomeric-Coated Composites, 500 MPH, 1 Inch/Hour Rainfall

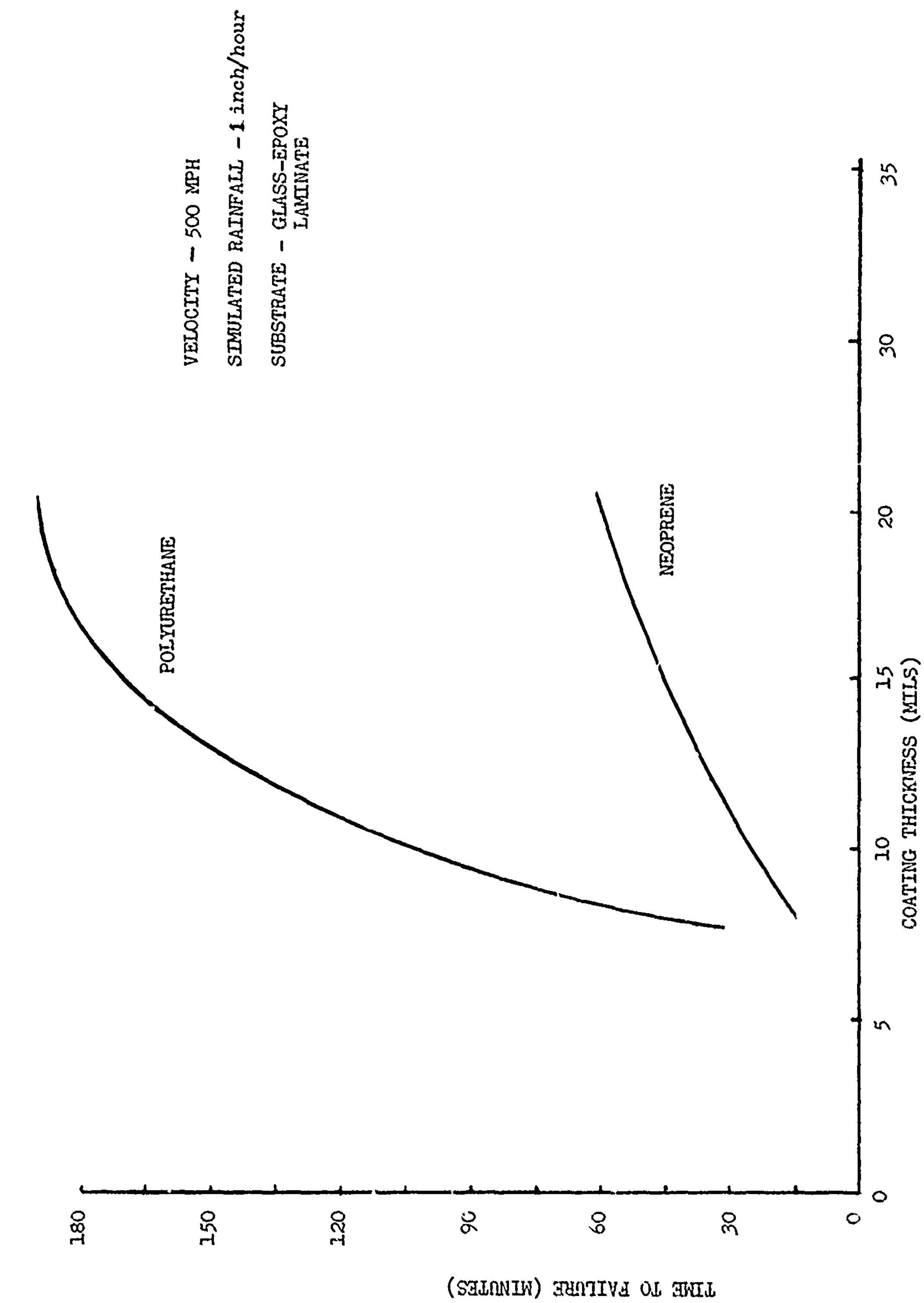


Figure 5. Comparison of Polyurethane vs. Neoprene Performance in Rotating Arm Apparatus

Since the normal stress (σ_f) and the normal particle velocity (u_f) must be the same on either side of the coating-substrate interface, the equations of momentum discontinuity may be written as follows:

$$\sigma_f = \rho_S C_S u_f \quad \text{(for shock in the substrate)}$$

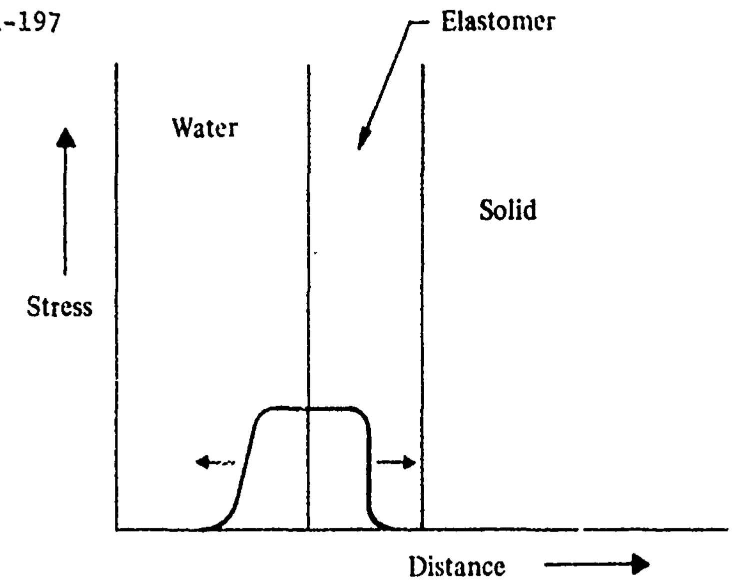
where ρ_s and C_s are density and shock propagation speed in the substrate, and

$$(\sigma_f - \sigma_i) = \rho_C C_C (u_f - u_i) \quad \text{(for shock in the coating)}$$

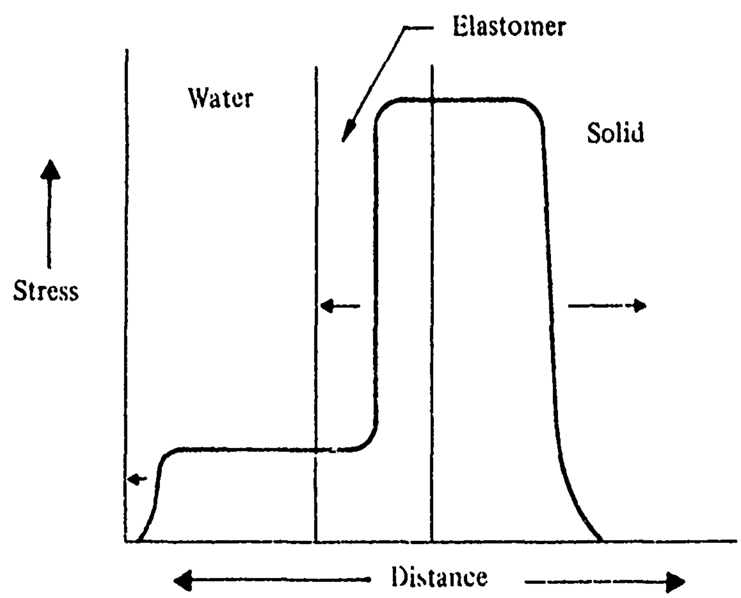
where σ_i and u_i are the normal stress and the particle velocity initially and ρ_c and C_c are the density and shock propagation speed in the coating. These equations may be solved for σ_f and u_f.

The course of water droplet impact on a urethane-coated substrate is shown in Figures 6(a) and (b). The initial stress pulse delivered to the elastomer is low and propagates toward the coating-substrate interface. When it strikes this interface, an intensified pulse is reflected back from the surface and is also transmitted into the substrate. The initial pulse is of the order of 33,700 psi for water impact at 500 mph with approximately 61,000 psi transmitted into the substrate. These values for loads are based upon the assumption that (1) the coating is so thin that the uniaxial deformation wave established on initial contact is not attenuated before striking the interface (2) the build-up of applied load during impact of the droplet may be ignored and (3) the finite strength of the elastomer may be ignored.

A similar analysis has been performed for a hard coating i. e., nickel, on a lower modulus substrate. The initial stress pulse in this case is quite high because of the high modulus of the coating. This



a. Stress Distribution before the Stress Pulse Reaches the Solid Surface (Arrows Indicate Propagation Direction)



b. Stress Distribution Shortly after the Stress Wave Impinges on the Solid-Elastomer Interface

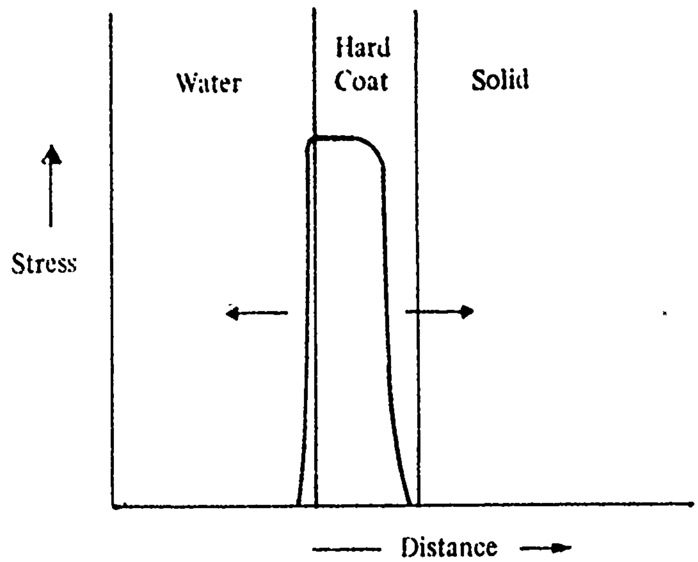
Figure 6. Water Impact on a Solid Coated with a Thin Elastomeric Layer: Stress Distribution Along the Line of Contact (Arbitrary Units)

modulus is greater than that of the substrate which it is protecting. When the pulse strikes the interface, it is relieved and a low level pulse is reflected back into the coating as well as being transmitted into the substrate. The course of the water droplet impact for this case is shown in Figures 7(a) and (b). The initial load delivered to the higher modulus nickel approximates 60,400 psi while that transmitted to the substrate is 34,800 psi.

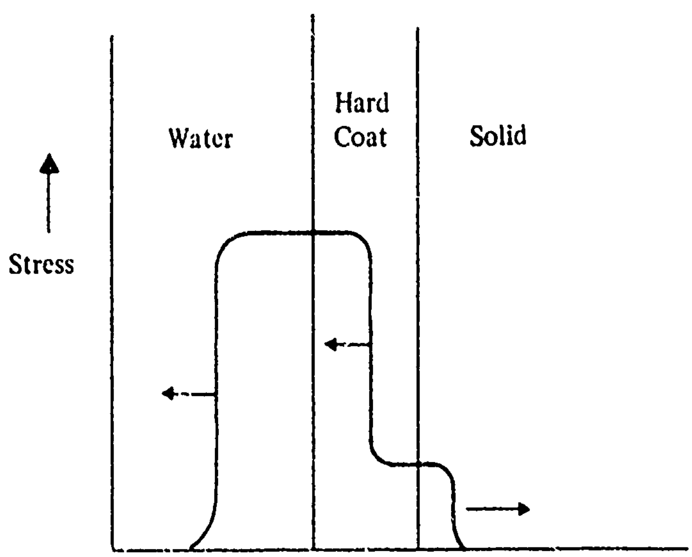
A hard metal such as nickel or ceramic coating thus offers comprehensive protection by shielding the substrate from the impact load and the radially flowing droplet (See Figure 8). If an adhesive layer of low acoustic impedance is underneath the coating, the adhesive is also protected.

The values here are based upon aluminum substrates but similar values would apply to composites also and are verified by the experimental results.

The above analysis describes the phenomena observed with urethane- and nickel-coated composites of glass, graphite and boron-fiber reinforcement. The urethane coatings transmit a large pressure pulse to the substrates resulting in failure of the composite beneath the coating. For a glass-reinforced, epoxy resin composite, the long exposures under the repeated droplet impacts are transmitted through the urethanes causing delamination of subsurface plies in the laminate. Because graphite fibers are prone to powdering (due to low transverse strength), they fail and form pockets of powdered fibers under the coating. In

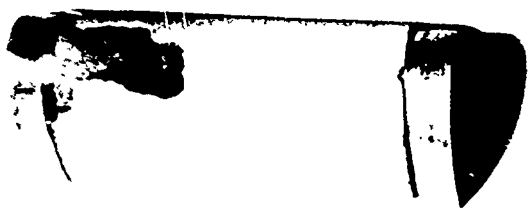


a. Stress Distribution before Stress Reaches the Coating-Solid Interface (Arrows Indicate Propagation Direction)

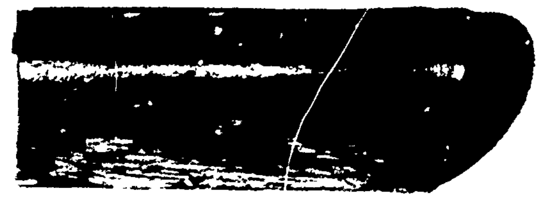


b. Stress Distribution Shortly after the Stress Wave Impinges on the Coating-Solid Interface

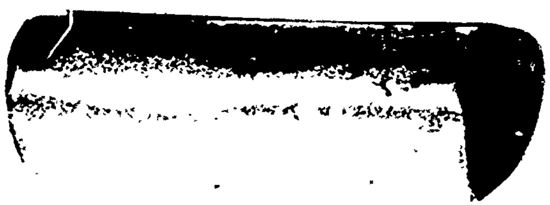
Figure 7. Water Impact on a Solid Coated with a Thin, Hard Coating: Stress Distribution Along the Line of Contact (Arbitrary Units)



PLASMA SPRAYED ALUMINA/ALUMINUM
44.5 MINUTES



ELECTROPLATED HARD NICKEL/
GRAPHITE-EPOXY COMPOSITE
196 MINUTES



ELECTROFORMED HARD NICKEL/GRAPHITE-
EPOXY COMPOSITE
200 minutes

ELECTROPLATED NICKEL/GLASS-EPOXY
[illegible]60 MINUTES

Figure 8. Ceramic and Metallic Coated Specimens,
500 MPH, 1 Inch/Hour Rainfall

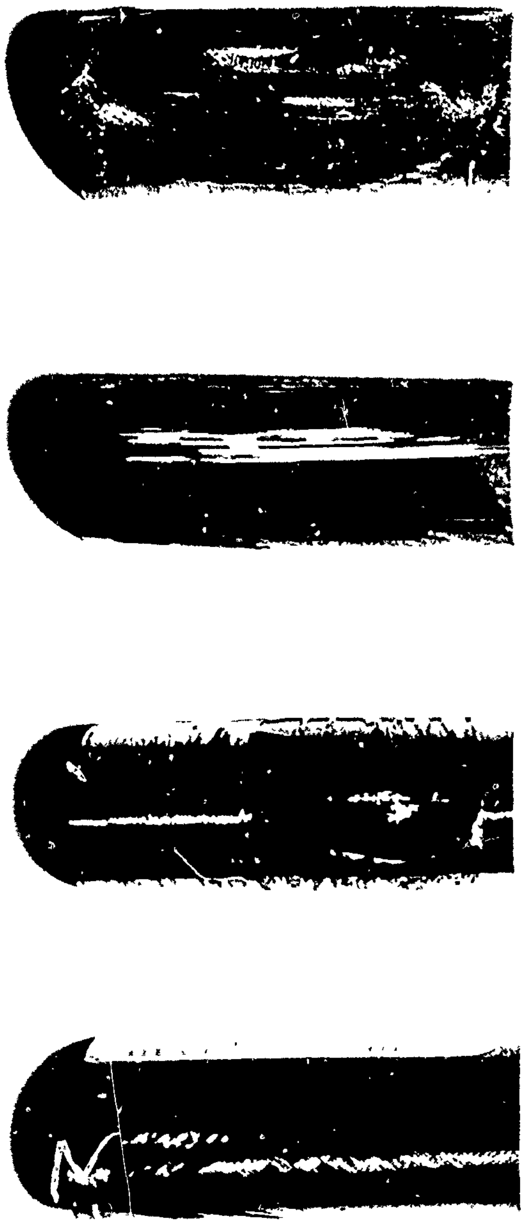
contrast, the boron fibers do not powder, and the urethane-coated boron composites fail at a weak point in the structure or at a point where the matrix resin is crushed by the repeated droplet blows.

Under the nickel coatings, the composites of glass, graphite and boron exhibit no powdering or substantial substrate crushing in keeping with the low pressure pulse transmitted to the substrate. A failure in this case occurs at a void location in the composite or at a spot of adhesion loss of the plating to the composite. This then results in a "boring-in" at that point with a deep hole rather than a widening of the hole or further penetration locations through the coating.

Typical erosion damage on uncoated and coated graphite- and boron-epoxy composites is shown in Figures 9 through 12.

Effect of Coating Modulus and Other Properties

Recent experiments with a split Hopkinson pressure bar apparatus at strain rates of 10^3 sec^{-1} have been conducted on elastomeric and rigid plastic materials to investigate their response to loading rates comparable to those associated with rain droplet impact at subsonic speeds (Reference 5). Although there is question as to the precise applicability of this device, for simulating droplet impacts, these investigations demonstrate that because typical coatings properties measurements (elongation, tensile strength, modulus) are made at loading rates which are orders of magnitude less than that associated with droplet impact, little correlation is obtained between these measurements, and rain erosion resistance. This lack of correlation



SPECIMEN 1524
BORON - EPOXY
15 MINUTES

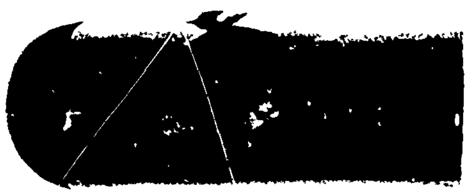
SPECIMEN 1691
BORON - EPOXY
2.0 MINUTES

SPECIMEN 1690
GRAPHITE - EPOXY
1.0 MINUTE

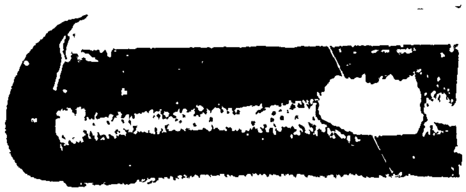
SPECIMEN 1723
GRAPHITE - EPOXY
0.6 MINUTE

Figure 9. Uncoated Composite Erosion, 500 MPH, 1 Inch/Hour Rainfall

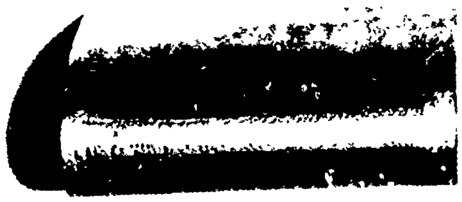
SPECIMEN 1525
0.012" POLYURETHANE COATING
47.5 MINUTES



SPECIMEN 1528
0.012" POLYURETHANE COATING
43.8 MINUTES

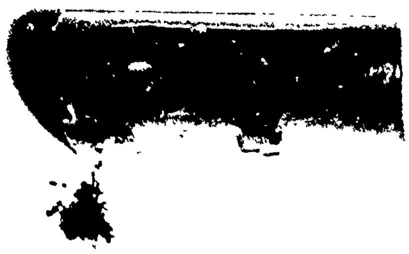


SPECIMEN 1530
0.008" ELECTROPLATED NICKEL COATING
104.0 MINUTES

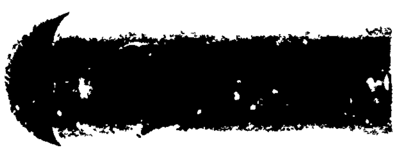


SPECIMEN 1532
0.008" ELECTROPLATED NICKEL COATING
110.0 MINUTES

Figure 10. Boron-Epoxy Composite Erosion, 500 MPH, 1 Inch/Hour Rainfall



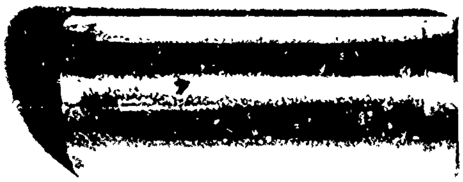
SPECIMEN 1785
0.012" POLYURETHANE COATING
9.6 MINUTES
NOTE POWDERING
(COATING HAS BEEN CUT OPEN)



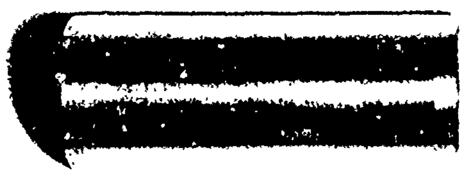
SPECIMEN 1781
0.012" POLYURETHANE COATING
7.8 MINUTES
NOTE RIDGE OF POWDERED CARBON
BENEATH COATING (AT LEFT)

SPECIMEN 1972
0.012" POLYURETHANE COATING
12.2 MINUTES
NOTE ADHESION LOSS AND TEARING OF COATING
AFTER SUBSTRATE POWDERING

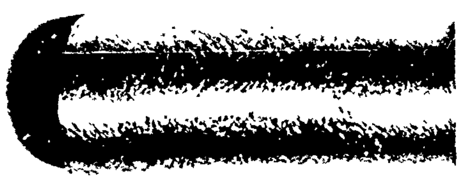
Figure 11. Graphite-Epoxy Composite Erosion, 500 MPH, 1 Inch/Hour Rainfall



SPECIMEN 1925
0.009" ELECTROPLATED NICKEL (BONDED)
180 MINUTES
NOTE SMALL HOLE



SPECIMEN 1811
0.006" ELECTROFORMED NICKEL (HARD)
(ADHESIVELY BONDED)
60 MINUTES



SPECIMEN 1314
0.006" ELECTROPLATED NICKEL (HARD)
(DIRECTLY DEPOSITED)
120 MINUTES

SPECIMEN 1881
0.006" ELECTROPLATED NICKEL
196.1 MINUTES

Figure 12. Graphite-Epoxy Composite Erosion, 500 MPH, 1 Inch/Hour Rainfall

has been demonstrated even in the development of polyurethane coatings which are the most erosion resistant elastomeric coatings currently available (Reference 6).

Previous advancements in materials for erosion resistance have been possible because use of the rotating arm which directly simulates the rain droplet impingement at velocity in a multiple particle environment, has enabled a realistic and meaningful evaluation of their erosion behavior under appropriate dynamic conditions.

Several generalizations are possible concerning the requisite physical properties of a rain erosion resistant coating. The modulus of the coating should be low; that is, approximately 200 - 400 psi at 100% elongation. These properties have been exhibited by both polyurethanes and neoprenes (See Table II). The superiority of these coatings for erosion protection is also due to their high elongation (700% or greater) which imparts resiliency and ability to recover from the impact. It is this combination of conventionally measured properties which is required in a polymeric-based erosion protective coating.

Other properties such as shear strength, abrasion resistance, and tear resistance have little relation to the response of polymeric coatings in a rain droplet environment (Reference 6).

Comparison of the times to failure in the erosion environment and the physical properties of selected polymeric coatings are shown in Table II.

Effect of Coating Hardness

A brief investigation was conducted of the effect of coating hardness in elastomeric coatings. This is not an isolated property since changing hardness in an elastomer also changes modulus, elongation and tensile strength. Three polyether-based, clear polyurethanes were examined and their physical properties and erosion performance are summarized in Table III. As may be seen no clear-cut correlation exists between the hardness of an elastomeric coating and its subsonic rain erosion resistance. The time-to-failure for the Shore A-90- and D-58-hardness polyurethanes are comparable and quite low. Although the time to failure for the D-70 hardness polyurethane is considerably higher, the blistering and cracking mode of failure for this material indicates that its hardness is high enough to induce some brittleness relative to the water droplet impact.

Despite the high values for tensile strength, elongation and modulus for these polyurethanes, their performance in the rain environment does not compare with the polyether-base, moisture-set, low modulus polyurethanes of the type which has shown outstanding erosion performance. (See Table III).

SECTION IV

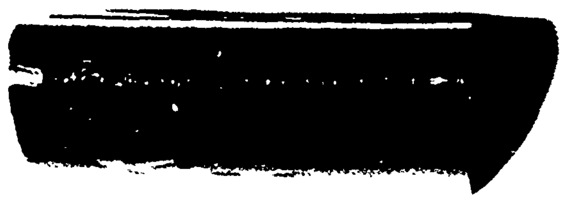
POLYMERIC COMPOSITES EROSION BEHAVIOR

The erosion of glass fiber-reinforced composites in the rotating arm rain environment is usually uniform and consistent. Typically a number of layers of cloth would be removed along with the impregnating resin. Representative damage is shown in Figure 13 for uncoated composites.

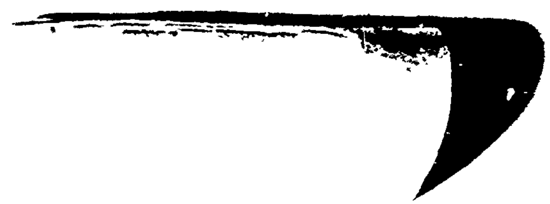
Effects of Reinforcement vs Homogeneity

The influence of reinforcement was investigated in two types of resins. The low void glass-polyimide laminates had exhibited relatively good resistance compared to other resin laminates and so it was also decided to run cast (unreinforced) polyimide resins. Polyimide resins are brittle by nature and fracture of these materials by the droplet impact was expected. This was borne out in rotating arm tests where an unreinforced polyimide airfoil 0.125 in. thick was completely eroded through its entire thickness in 10 minutes at 500 mph, 1 inch/hour rain, while a glass reinforced version was only penetrated to a depth of 0.040 in. in the same exposure.

In a brittle material, the beneficial effect of strengthening by reinforcement results in improved subsonic erosion resistance, because the presence of the fibers reduces chunking out and breakage into small pieces by providing a discontinuous path for shock transmission through the material. This behavior is observed for any thermosetting-resin, homogeneous-versus-composite material.



LOW VOID GLASS - POLYIMIDE LAMINATE
4.7 MINUTES
(PARTIAL EROSION OF FIRST PLY)



GLASS- EPOXY LAMINATE
5.0 MINUTES
(ERODED THROUGH [illegible] PLIES)

POLYPHENYLENE OXIDE-GLASS LAMINATE
3.1 MINUTES
(ERODED THROUGH 3 PLIES)

GLASS_EPOXY LAMINATE
[illegible] MINUTES
(PARTIAL EROSION OF FIRST PLY)

Figure 13. Uncoated Composites, 500 MPH,
1 Inch/Hour Rainfall

However, the addition of reinforcement to a thermoplastic material which is inherently erosion resistant such as cast polyphenylene oxide (PPO) or nylon resins results in increased erosion upon exposure. Bulk polyethylene or nylon exhibit a sufficiently plastic response to the impinging droplet loads to deform on the surface with little weight loss during the subsonic exposure times on these tests. However, if reinforcement is added, the radially flowing, compressed portion of the impinging drop interacts with the fiber reinforcement and breaks out pieces of fiber and matrix. This data is tabulated in Appendix I and plots of weight loss versus exposure time are shown in Figures 16 through 25.

The following observations were made:

a. At 500 MPH, the ranking of the unreinforced polymers in terms of decreasing rain erosion resistance was polyethylene, acetal, and nylon in that order. The rankings did not change at 600 MPH although the performance of the three bulk polymers was closer.

b. There was no apparent difference in the bulk acetal with or without U.V. Stabilizers.

c. The addition of chopped fiber reinforcement to the polyethylene resulted in an order of magnitude increase in weight loss after the same exposure.

d. The addition of reinforcement to the nylon did not increase the weight loss but appeared to reduce it slightly. However, within the scatter of the data the effect of reinforcement with the nylon was negligible.

From the above experiments, the unreinforced polyethylene Alathon 7050, NC-10 gave the best performance. The utility of these materials for protection of the front end of a radome such as by molding a protective cap appears limited because of their thermal limitations, the detrimental effect of reinforcement (which might be necessary structurally) and their erosion performance which was only fair-to-good.

The morphology of the bulk resins appears to strongly influence their erosion behavior. Although not specifically investigated there is some indication that the degree of crystallinity or amorphousness of the bulk polymer may control its erosion resistance. If appropriate control over the degree of crystallinity can be established, it may be possible to manufacture plastics which are highly resistant.

Effects of Matrix Resin

In addition to the influence of the reinforcement, the erosion behavior of a glass-reinforced laminate depends to a large extent on the type of resin which serves as the matrix for the composite. This was particularly noted in the poor performance of the higher temperature organic resin laminates such as polybenzimidazole, polyimide (high voids), and silicone during supersonic rocket sled investigations on the Holloman AFB track (Reference 7). The data and performance of these composites is discussed extensively in Reference 7 and the following comments are included for completeness of the discussion on polymeric composite behavior.

These resins provide a high temperature (up to 600°F) capability but result in a composite with high void content (15%) and low erosion

resistance, which is a function of their brittle nature; this is in contrast to the erosion resistance of low void epoxy, polyimide, and polyester resin composites which although brittle do not fail as catastrophically. The resulting composites of high temperature organic matrix materials are relatively low in modulus of elasticity (2.7 to 2.88×10^6 psi) and compressive strength (6 to 28×10^3 psi) and the lack of these properties contributes to their severe erosion in the subsonic environment. By contrast, the epoxy and polyphenylene oxide resin-based plastic composites have moderate-to-high moduli and compressive strengths coupled with low porosity and exhibit better performance in the rain environment. (See Table IV for properties).

The influence of matrix resin is not as significant if the void content of the composite is reduced to 3% or less.

Effects of Void Content

The void content of a composite can significantly influence its erosion behavior because the high void content composites possess lower strength properties and hence will not withstand the erosive environment even when coated. This is demonstrated in the erosion of a high void polyimide-glass laminate versus a low void polyimide-glass. The high void ($\sim$ 15%) construction was typical of polyimide laminates until improvements in processing or chemical modification of the resin enabled attainment of low void content ($<$ 2%) in these laminates.

The strong influence of void content was also demonstrated in glass-epoxy substrates both unprotected and coated with neoprene and polyurethane coatings. Even with these coatings of demonstrated erosion

resistance, a glass-epoxy composite substrate of 10% void content resulted in failures of the coatings in 1/8 to 1/10 of the time compared to a low void (< 2%) glass-epoxy protected with identical coatings. Furthermore, with the polyurethane coatings, the crushing of the high void glass-epoxy underneath was great enough to cause cracking along the surface of the polyurethane. This is not a typical mode of erosion failure for polyurethanes which usually fail at an isolated point.

Table V shows the difference in erosion behavior between low void and high void composites of E glass cloth-polyimide and 181S glass-epoxy both uncoated and protected with elastomeric and metallic coatings.

Effects of Construction

An interesting comparison of the construction method of composites and the orientation of fibrous reinforcement was also conducted. Randomly-oriented, chopped glass fibers (20% by volume) such as are used in molded plastic parts were investigated in a polyimide resin matrix. When compared to conventional 2-D multi-ply E glass cloth layup (69% by volume), the erosion rates for this construction were greater than for the conventional laminate. See Table VI for this data. For a given glass fiber volume concentration, the two-dimensional laminate construction would provide better reinforcement than the random chopped glass fibers because it provides a more continuous network to reduce the shock transmission (and hence, the breakage) through the composite.

The effects of random chopped fiber reinforcement vs. conventional 2-D reinforcement in a thermoplastic resin remain to be investigated.

The emphasis to date has been on thermosetting polymeric composites because they are used for aerospace structures due to their strength properties.

The thermoplastic resins deform more than the thermosetting materials, and the glass or other reinforcement-resin matrix interfacial bond is not as good with the thermoplastic polymers. Both of these factors will affect the composite properties and influence its erosion behavior.

Changing from a low void polyimide composite with E glass reinforcement to one which had quartz fiber reinforcement showed no essential difference in erosion behavior. In general, a minor change like that or in lay-up technique, for example, 0°, $\pm 45^{\circ}$, or 90° in boron- or graphite-epoxy composites had little effect on the erosion behavior (Reference 8).

Another construction method investigated was the orientation of all glass fibers perpendicular to the surface in a close packed configuration with a high percentage of glass (> 80%) compared to the epoxy matrix resin. The resulting modulus in the direction of droplet impact was quite high because the end-on fibers (in a percentage) impart a high level of strength in a direction perpendicular to the surface (parallel to fiber length). Severe breakage and edge effects were noted on the higher angle portions of the airfoil specimens. This breakage was associated with areas where segments of perpendicularly-oriented,

glass-epoxy were fastened together to form the specimens. This points out the criticality of integration into an actual shape of a possible erosion resistant construction technique.

When specimens were fabricated which overcame the segmented difficulty, severe erosion was noted in low impact angle ($< 20^{o}$) areas caused by the radial flow of the impinging drop acting as a bending load on the fiber ends. The leading edges were relatively undamaged. See Figures 14 and 15 for this latter damage. The utilization of this type of construction would be most appropriate as the tip cap on a conventional lay-up or filament wound radome. However, in all cases it will still likely require an erosion protective coating.

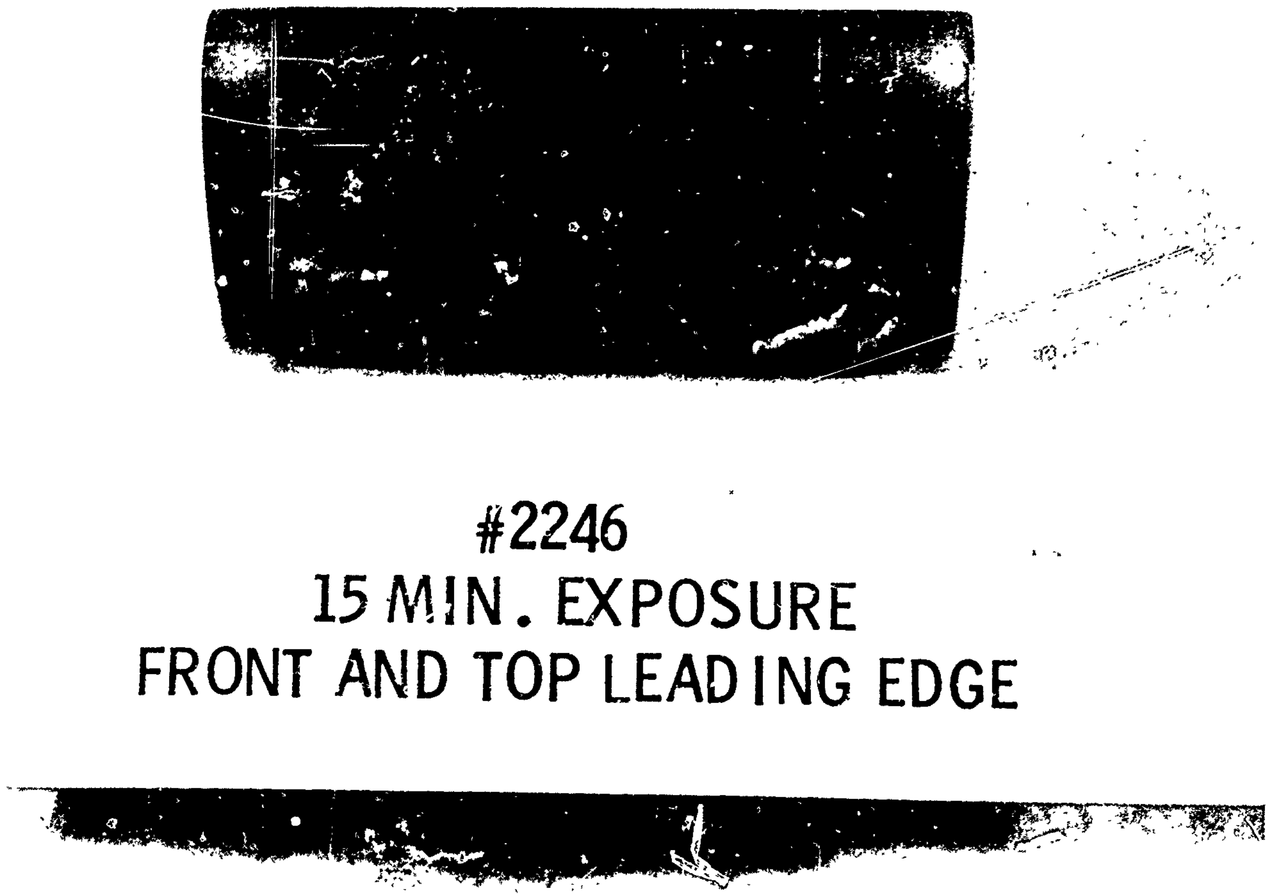
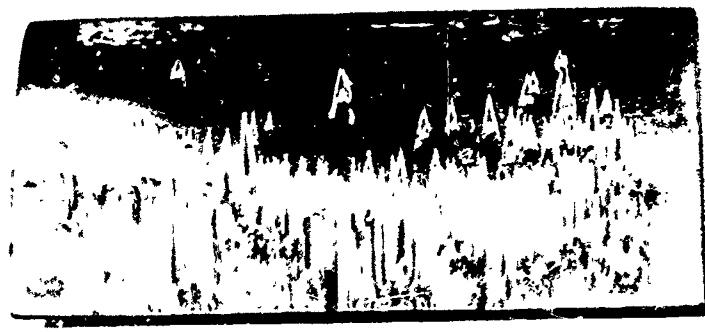


Figure 14. Leading Edge of Perpendicularly Oriented Glass-Epoxy Composite After 15 min @ 500 MPH, 1 Inch/Hour Rainfall



#2246
15 MIN. EXPOSURE
FRONT AND TOP LEADING EDGE

Figure 15. Low Impingement Angle Area of Perpendicularly Oriented Glass-Epoxy Composite After 15 min @ 500 MPH, 1 Inch/Hour Rainfall

SECTION V

DISCUSSION

The requisite properties for a polymeric rain erosion resistant coating have been mentioned previously. It must be elastomeric in nature with low modulus and high elongation required. The properties of these coatings at high loading rates such as are experienced in droplet impacts during actual flight encounter or rotating arm experiments govern the response of these coatings and their erosion resistance. The resiliency and ability to recover or reduce the stress pulse to the substrate are the keys to elastomeric coatings protective ability.

A reinforced polymeric composite must be protected from the rain environment by a protective coating for prolonged subsonic erosion protection. However, the erosion resistance of the overall coated composite can be enhanced if the following design rules are considered in the substrate.

a. The composite should include reinforcement if the resin is thermosetting.

b. Thermoplastic resins should incorporate as little reinforcement as is consistent with strength levels obtainable for structural considerations.

c. The void content of the composite must be minimized.

d. Glass cloth or fiber reinforcement produces more erosion resistant composites than do boron or graphite fibers.

e. The use of fibers oriented perpendicularly to the surface being impacted by droplets provides a substrate with more inherent resistance than conventional lay-ups.

In any erosion design or materials development, the overall system (i. e. coating and substrate) must be considered throughout. The initial designs for radomes or other exterior structural applications must incorporate an erosion protective coating. The development of protective materials must likewise utilize a substrate of the appropriate construction for materials screening and final verification testing. Only in this way can confidence in the erosion resistance of a material or subsystem be generated.

SECTION VI

CONCLUSIONS

1. Elastomeric coatings provide greater subsonic rain erosion protection than other brittle polymeric coatings because their stress-strain characteristics and Hugoniot response to the loading associated with droplet impact weaken the stress pulse and protect the substrate.

2. Metallic or hard ceramic coatings provide protection because their high modulus transmits only a very low stress pulse to the substrate.

3. All reinforced plastic materials require rain erosion protection even at subsonic velocities.

4. The addition of reinforcement whether conventional glass cloth lay-up or chopped fibers to a thermoplastic resin reduces its erosion resistance.

5. The fracture and brittle chunking behavior of a thermosetting polymer in the rain environment are considerably improved by the addition of reinforcement.

6. The void content and reinforcement type and orientation of organic matrix composites significantly influence their subsonic rain erosion behavior whether the composites are uncoated or coated for erosion protection.

SECTION VII

FUTURE WORK

1. The rotating arm apparatus will continue to be used for assessment of the erosion resistance of candidate coatings, bulk plastics and substrate constructions.

2. The detailed mechanisms of erosion behavior of ductile (1100 Aluminum), brittle (polymethylmethacrylate), and composite (glass-epoxy laminate) materials will be investigated at velocities up through Mach 1.2.

3. Effects of droplet size on the erosion behavior of bulk and composite materials and coatings will be examined.

4. The effect of polymer morphology will be investigated to determine the desirable degree of crystallinity or amorphousness to render a plastic more resistant to rain erosion.

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6. J. F. Moraveck and G. H. Clarke, Rain and Sand Erosion Resistant Polyurethane Protective Coatings, AFML-TR-67-227, Part II, July 1969.

7. G. F. Schmitt, Jr. and A. H. Krabill, Velocity Erosion Rate Relationships of Materials in Rain at Supersonic Velocities, AFML-TR-70-44, October 1970.

8. G. F. Schmitt, Jr. Rain Erosion Behavior of Graphite- and Boron-Fiber Reinforced Composite Materials, AFML-TR-70-316, March 1971.

APPENDIX I

WEIGHT LOSS DATA FOR BULK POLYMERS

TABLE I

BULK PLASTICS EROSION WEIGHT LOSS DATA

Specimen No.	Material	Velocity MPH	Init. Wgt.	Wgt. 5.0 min	Wgt. Loss	Wgt. 10.0 min	Wgt. Loss	Wgt. 15.0 min	Wgt. Loss	Wgt. 20.0 min
3076	XPI Injection Molded MC154 Polyimide (bulk)	500	18.1302	17.8797	0.2505	17.5870	0.5432	17.2198	0.9104	16.5997 Damaged
3077	XPI Injection Molded MC154 Polyimide (bulk)	500	18.2023	18.0559	0.1464	17.8554	0.3469	17.6489	0.5534	17.4055
3078	XPI Injection Molded MC154 Polyimide (bulk)	600	18.1255	17.7525	0.3730	17.5046	0.6209	17.1630	0.9625	Damaged 16.7497
3079	XPI Injection Molded MC154 Polyimide (bulk)	600	18.0962	17.8030	0.2932	17.6518	0.4444	Damaged 17.0749	1.0213	
3080	XPI Injection Molded MC154 Polyimide (20%vol. chopped fibers)	500	18.8105	18.6965	0.1140	18.5600	0.2505	18.4471	0.3634	18.3196
3081	XPI Injection Molded MC154 Polyimide (20% vol. chopped fibers)	500	18.7463	18.5980	0.1483	18.4708	0.2755	18.3547	0.3916	18.2192
3082	XPI Injection Molded MC154 Polyimide (20% vol. chopped fibers)	600	18.7619	18.5653	0.1966	18.4065	0.3554	18.1826	0.5793	17.9350
3083	XPI Injection Molded MC154 Polyimide (20% vol. chopped fibers)	600	18.6690	18.4175	0.2515	18.2287	0.4403	17.9686	0.7004	17.5897
3223	Zytel 151, NC-10 Unreinforced 612 Nylon	500	11.7773	11.7529	0.0244	Damaged 11.6244	0.1529	11.5895	0.1878	
3224	Zytel 151, NC-10 Unreinforced 612 Nylon	500	12.1971	12.1722	0.0249	12.1654	0.0317	12.1405	0.0566	Damaged 12.0391
3225	Zytel 151, NC-10 Unreinforced 612 Nylon	600	11.7463	11.7170	0.0293	Damaged 11.6180	0.1283	Damaged 10.9898	0.7565	
3226	Zytel 151, NC-10 Unreinforced 612 Nylon	600	12.2300	12.1997	0.0303	12.1902	0.0398	12.1492	0.0808	12.0875

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TABLE I

BULK PLASTICS EROSION WEIGHT LOSS DATA

min	Wgt. Loss	Wgt. 10.0 min	Wgt. Loss	Wgt. 15.0 min	Wgt. Loss	Wgt. 20.0 min	Wgt. Loss	Wgt. 25.0 min	Wgt. Loss	Wgt. 30.0 min	Wgt. Loss
97	0.2505	17.5870	0.5432	17.2198	0.9104	16.5997 Damaged					
59	0.1464	17.8554	0.3469	17.6489	0.5534	17.4055	0.7968	17.3951	0.8072	17.3643	0.8380
25	0.3730	17.5046	0.6209	17.1630	0.9625	Damaged 16.7497	0.4133				
30	0.2932	17.6518	0.4444	Damaged 17.0749	1.0213						
55	0.1140	18.5600	0.2505	18.4471	0.3634	18.3196	0.4911	18.1675	0.6430	17.9620	0.8485
0	0.1483	18.4708	0.2755	18.3547	0.3916	18.2192	0.5271	18.1835	0.5628	17.8683	0.8936
3	0.1966	18.4065	0.3554	18.1826	0.5793	17.9350	0.8269	17.5953	1.1666	17.5898	1.1721
5	0.2515	18.2287	0.4403	17.9686	0.7004	17.5897	1.0793				
[illegible]	0.0244	Damaged 11.6244	0.1529	11.5895	0.1878						
[illegible]	0.0249	12.1654	0.0317	12.1405	0.0566	Damaged 12.0391	0.1580				
[illegible]	0.0293	Damaged 11.6180	0.1283	Damaged 10.9898	0.7565						
[illegible]	0.0303	12.1902	0.0398	12.1492	0.0808	12.0875	0.1425	Damaged 11.4940			

TABLE I (CONT'D)

BULK PLASTICS EROSION WEIGHT LOSS DATA

Specimen No.	Material	Velocity MPH	Init. Wgt.	Wgt. 5.0 min	Wgt. Loss	Wgt. 10.0 min	Wgt. Loss	Wgt. 15.0 min	Wgt. Loss	W[illegible] 20.[illegible]
3227	Zytel 7710-33 33% Glass 612 Nylon	500	14.6188	14.5987	0.0201	14.5940	0.0248	14.5896	0.0292	14.5[illegible]
3228	Zytel 7710-33 33% Glass 612 Nylon	500	15.0412	15.0205	0.0207	15.0155	0.0257	15.0111	0.0301	15.0[illegible]
3229	Zytel 7710-33 33% Glass 612 Nylon	600	14.6776	14.6527	0.0249	14.6473	0.0303	14.6305	0.0471	14.6[illegible]
3230	Zytel 7710-33 33% Glass 612 Nylon	600	14.9808	14.9553	0.0255	14.9475	0.0333	14.9310	0.0498	14.9[illegible]
3231	Alathon 7050, NC-10 Unreinforced Polyethylene	500	10.5327	10.5331	0.0004	10.5315	0.0012	10.5300	0.0027	10.5[illegible]
3232	Alathon 7050, NC-10 Unreinforced Polyethylene	500	10.6540	10.6546	0.0006	10.6530	0.0010	10.6523	0.0027	10.6[illegible]
3233	Alathon 7050, NC-10 Unreinforced Polyethylene	600	10.4350	10.4309	0.0041	10.4279	0.0071	10.4228	0.0122	10.5[illegible]
3234	Alathon 7050, NC-10 Unreinforced Polyethylene	600	10.7188	10.7152	0.0036	10.7108	0.0080	10.7055	0.0133	10.6[illegible]
3235	Alathon G-0350 30% Glass Polyethylene	500	12.7417	12.7093	0.0324	12.6628	0.0789	12.6276	0.1141	12.5[illegible]
3236	Alathon G-0350 30% Glass Polyethylene	500	13.2270	13.1977	0.0293	13.1400	0.0870	13.0803	0.1467	12.9[illegible]
3237	Alathon G-0350 30% Glass Polyethylene	600	13.2032	13.2032	0.0000	13.1508	0.0524	13.0575	0.1457	12.8[illegible]
3238	Alathon G-0350 30% Glass Polyethylene	500	12.7397	12.7390	0.0007	12.7064	0.0333	Damaged 12.6286	0.1111	
3239	Delrin 500 Unreinforced Acetal	500	15.6280	15.6195	0.0085	15.6150	0.0130	15.6125	0.0155	15.6[illegible]
3240	Delrin 500 Unreinforced Acetal	500	15.5185	15.5102	0.0083	15.5059	0.0126	15.5035	0.0150	15.5[illegible]

TABLE I (CONT'D)

BULK PLASTICS EROSION WEIGHT LOSS DATA

...it. ...gt.	Wgt. 5.0 min	Wgt. Loss	Wgt. 10.0 min	Wgt. Loss	Wgt. 15.0 min	Wgt. Loss	Wgt. 20.0 min	Wgt. Loss	Wgt. 25.0 min	Wgt. Loss	Wgt. 30.0 min	Wgt. Loss
...188	14.5987	0.0201	14.5940	0.0248	14.5896	0.0292	14.5875	0.0313	14.5822	0.0366	14.5687	0.0501
...412	15.0205	0.0207	15.0155	0.0257	15.0111	0.0301	15.0094	0.0318	15.0040	0.0372	14.9897	0.0515
...776	14.6527	0.0249	14.6473	0.0303	14.6305	0.0471	14.6207	0.0569	14.6155	0.0621	14.5975	0.0801
...808	14.9553	0.0255	14.9475	0.0333	14.9310	0.0498	14.9206	0.0602	14.9134	0.0665	14.8927	0.0881
...327	10.5331	0.0004	10.5315	0.0012	10.5300	0.0027	10.5288	0.0039	10.5260	0.0067	10.5248	0.0079
...540	10.6546	0.0006	10.6530	0.0010	10.6523	0.0027	10.6510	0.0030	10.6485	0.0055	10.6468	0.0072
...350	10.4309	0.0041	10.4279	0.0071	10.4228	0.0122	10.5152	0.0208	10.4038	0.0312	10.3951	0.0399
...88	10.7152	0.0036	10.7108	0.0080	10.7055	0.0133	10.6965	0.0223	10.6833	0.0355	10.6748	0.0440
...17	12.7093	0.0324	12.6628	0.0789	12.6276	0.1141	12.5787	0.1630	12.4862	0.2555		
...70	13.1977	0.0293	13.1400	0.0870	13.0803	0.1467	12.9957	0.2313	Damaged 12.8987			
...32	13.2032	0.0000	13.1508	0.0524	13.0575	0.1457	12.8927	0.3283	Damaged 12.8158	0.3874		
...97	12.7390	0.0007	12.7064	0.0333	Damaged 12.6286	0.1111						
...80	15.6195	0.0085	15.6150	0.0130	15.6125	0.0155	15.6151	0.0129	15.6114	0.0166		
...85	15.5102	0.0083	15.5059	0.0126	15.5035	0.0150	15.5052	0.0133	15.5020	0.0165		

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TABLE I (CONT'D)

BULK PLASTICS EROSION WEIGHT LOSS DATA

Specimen No.	Material	Velocity MPH	Init. Wgt.	Wgt. 5.0 min	Wgt. Loss	Wgt. 10.0 min	Wgt. Loss	Wgt. 15.0 min	Wgt. Loss
3241	Delrin 500, NC-10 Unreinforced Acetal	600	15.7659	15.7531	0.0128	15.7492	0.0167	15.7455	0.0204
3242	Delrin 500, NC-10 Unreinforced Acetal	600	15.3381	15.3263	0.0118	15.3234	0.0147	15.3200	0.0181
3243	Delrin 507, GY616 Unreinforced U.V. Stabilized Acetal	500	15.6299	15.6207	0.0092	15.6173	0.0126	15.6147	0.0152
3244	Delrin 507, GY616 Unreinforced U.V. Stabilized Acetal	500	15.6072	15.5983	0.0089	15.5940	0.0132	15.5915	0.0157
3245	Delrin 507, GY616 Unreinforced U.V. Stabilized Acetal	600	15.8256	15.8122	0.0134	15.8095	0.0161	15.8055	0.0201
3246	Delrin 507, GY616 Unreinforced U.V. Stabilized Acetal	600	15.4001	15.3878	0.0123	Damaged 15.2897	0.1104	Damaged 15.2617	0.1384

TABLE I (CONT'D)

BULK PLASTICS EROSION WEIGHT LOSS DATA

Wgt. 5.0 min	Wgt. Loss	Wgt. 10.0 min	Wgt. Loss	Wgt. 15.0 min	Wgt. Loss	Wgt. 20.0 min	Wgt. Loss	Wgt. 25.0 min	Wgt. Loss	Wgt. 30.0 min	Wgt. Loss
15.7531	0.0128	15.7492	0.0167	15.7455	0.0204	15.7403	0.0256				
15.3263	0.0118	15.3234	0.0147	15.3200	0.0181	15.3088	0.0293	Damaged 15.2230	0.1151		
15.6207	0.0092	15.6173	0.0126	15.6147	0.0152	15.6122	0.0177				
15.5983	0.0089	15.5940	0.0132	15.5915	0.0157	15.5895	0.0177				
15.8122	0.0134	15.8095	0.0161	15.8055	0.0201	15.8025	0.0231				
15.3878	0.0123	Damaged 15.2897	0.1104	Damaged 15.2617	0.1384						

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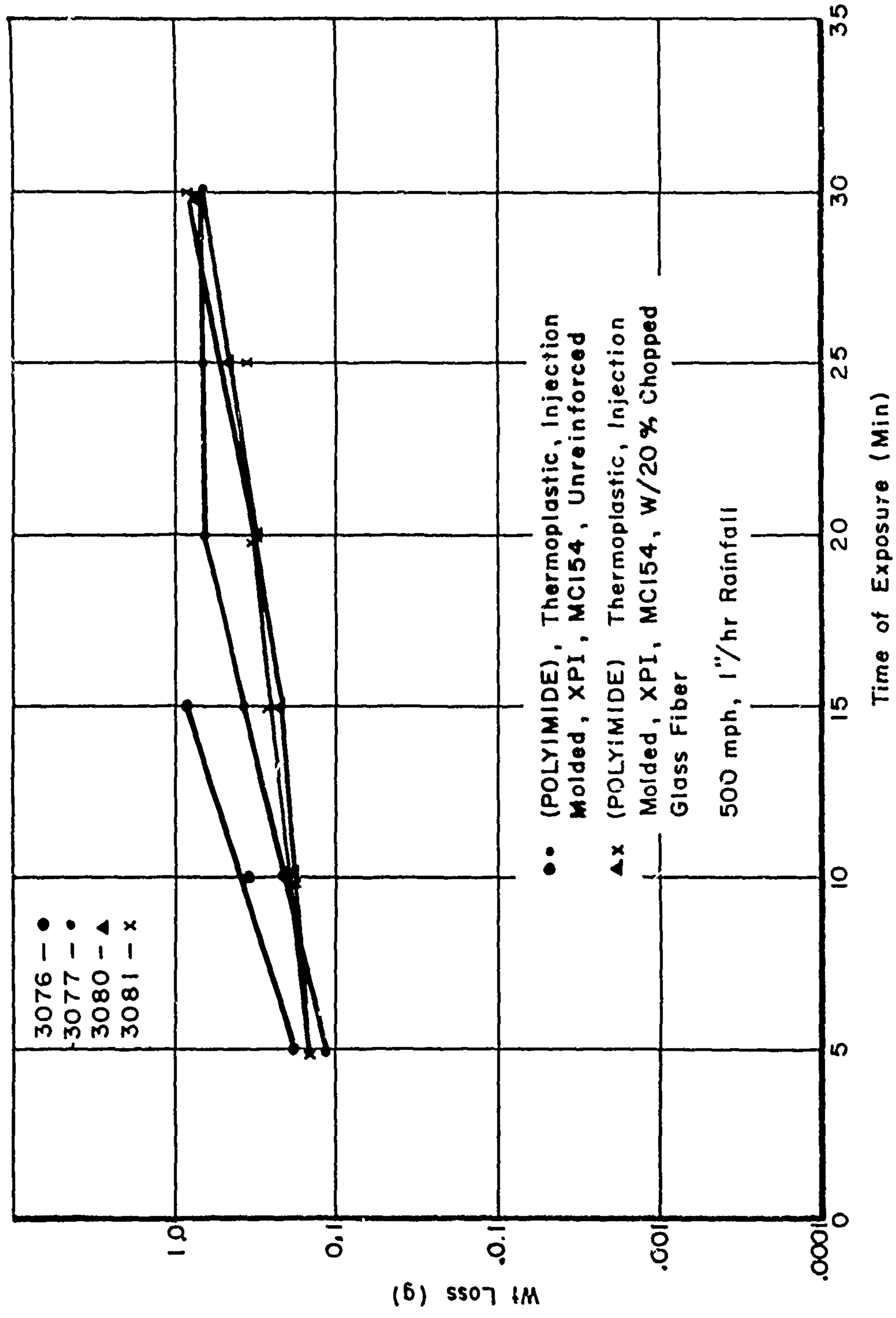

Figure 16. Reinforced vs. Unreinforced Thermoset Polyimide Weight Loss Data (500 MPH) 1 Inch/Hour Rainfall

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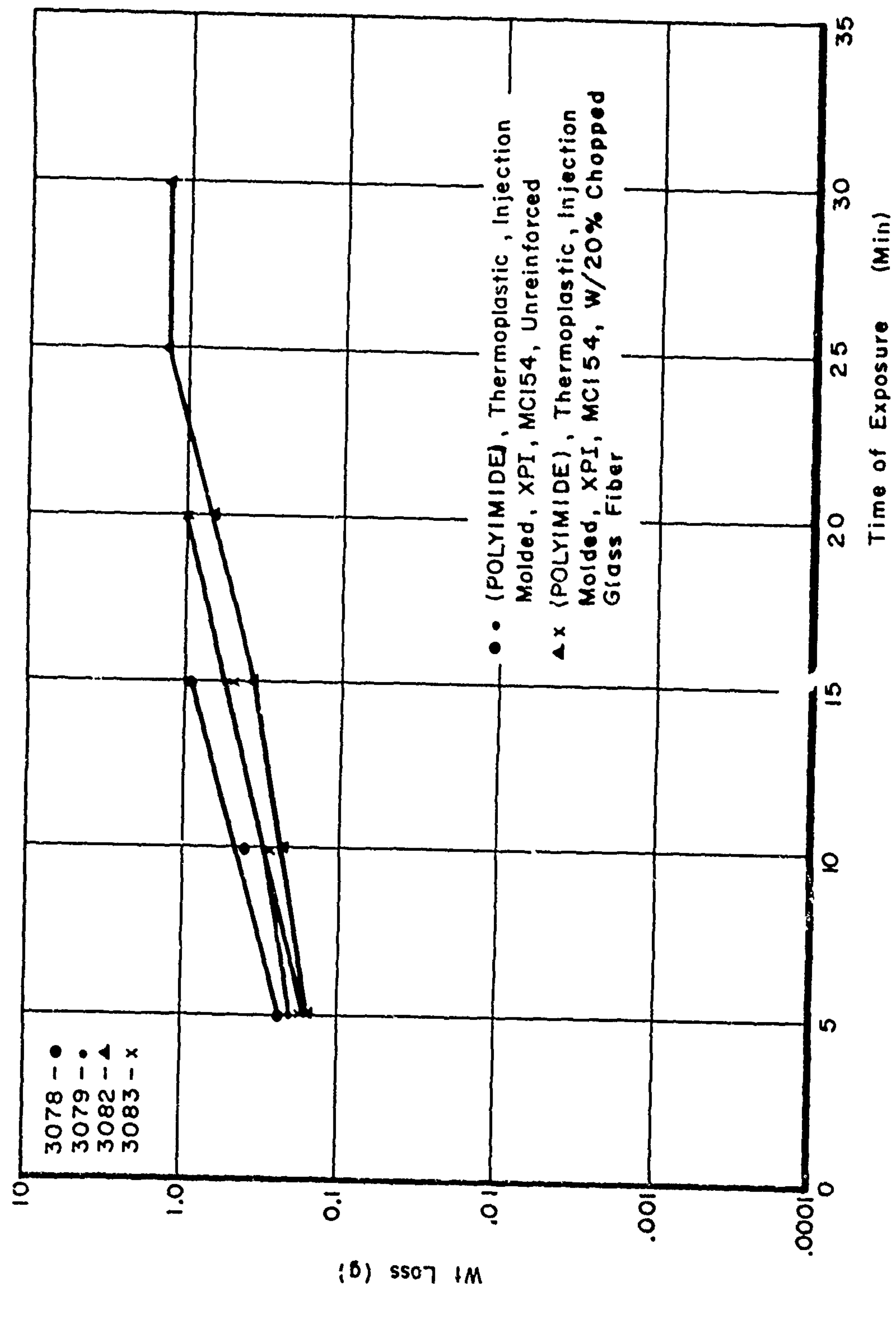

Figure 17. Reinforced vs. Unreinforced Thermoset Polyimide Weight Loss Data (600 MPH) 1 Inch/Hour Rainfall

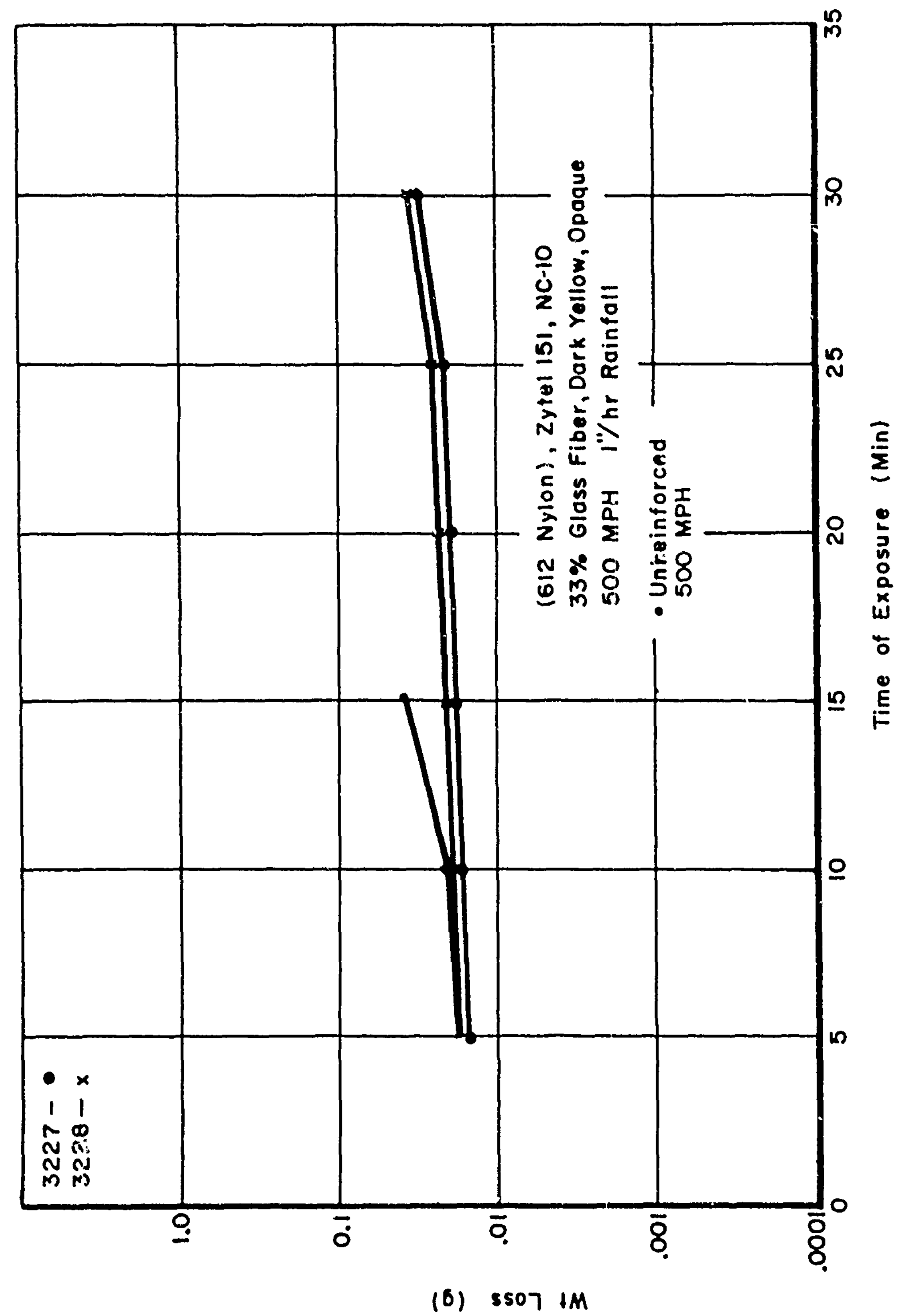

Figure 18. Reinforced vs. Unreinforced Thermoplastic Nylon Weight Loss Data (500 MPH) 1 Inch/Hour Rainfall

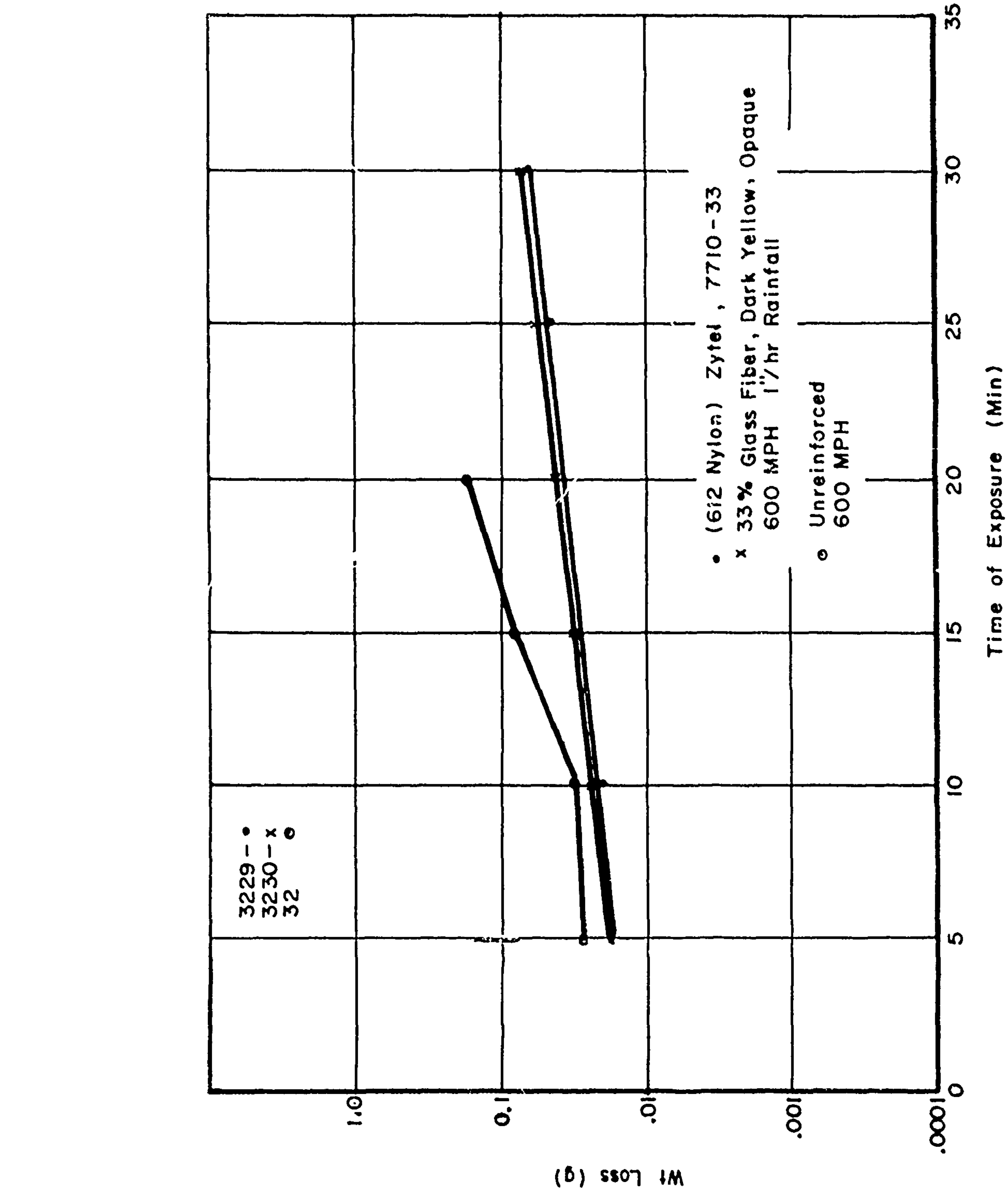

Figure 19. Reinforced vs. Unreinforced Thermoplastic Nylon Weight Loss Data (600 MPH) 1 Inch/Hour Rainfall

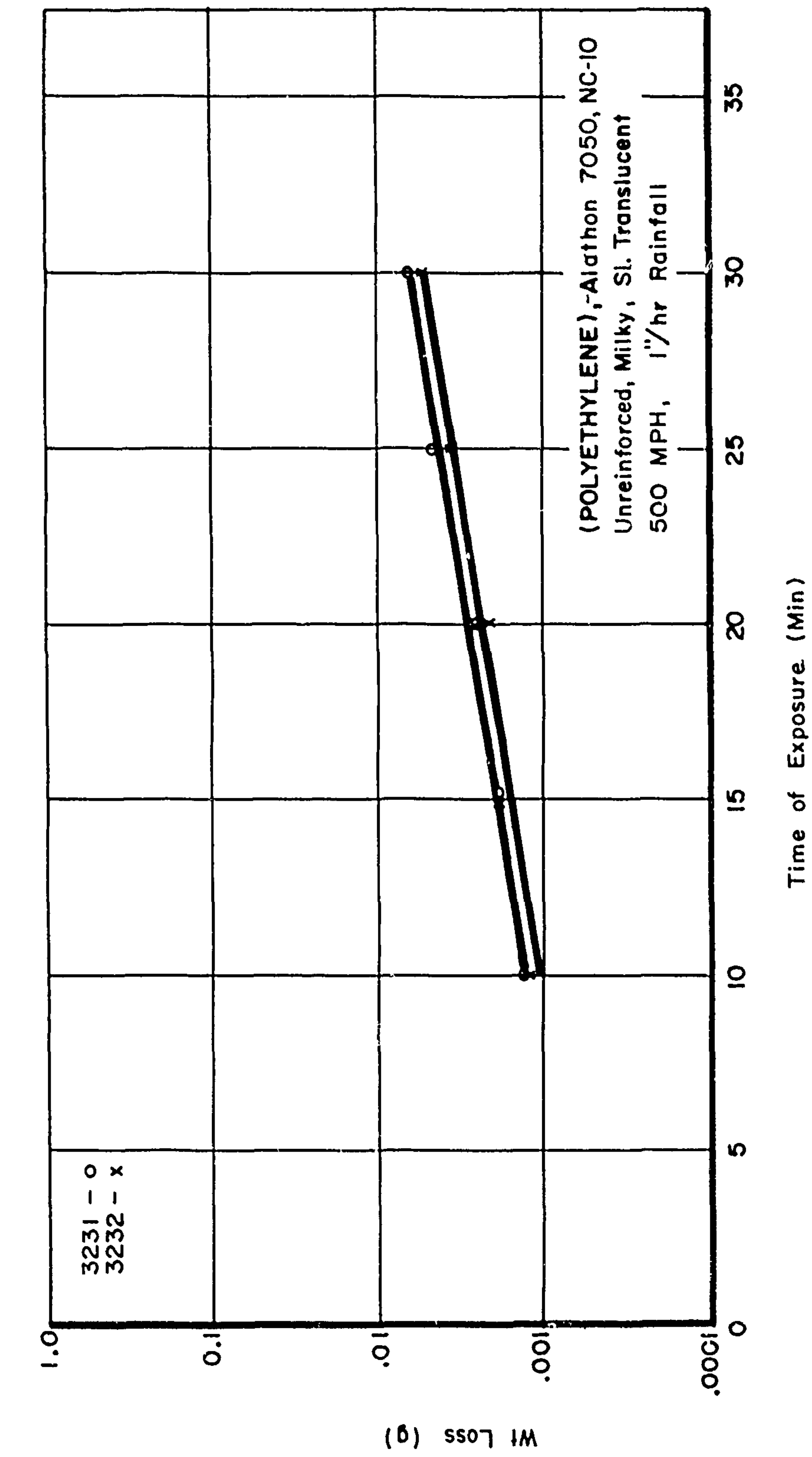

Figure 20. Unreinforced Polyethylene Weight Loss Data
(500 MPH) 1 Inch/Hour Rainfall

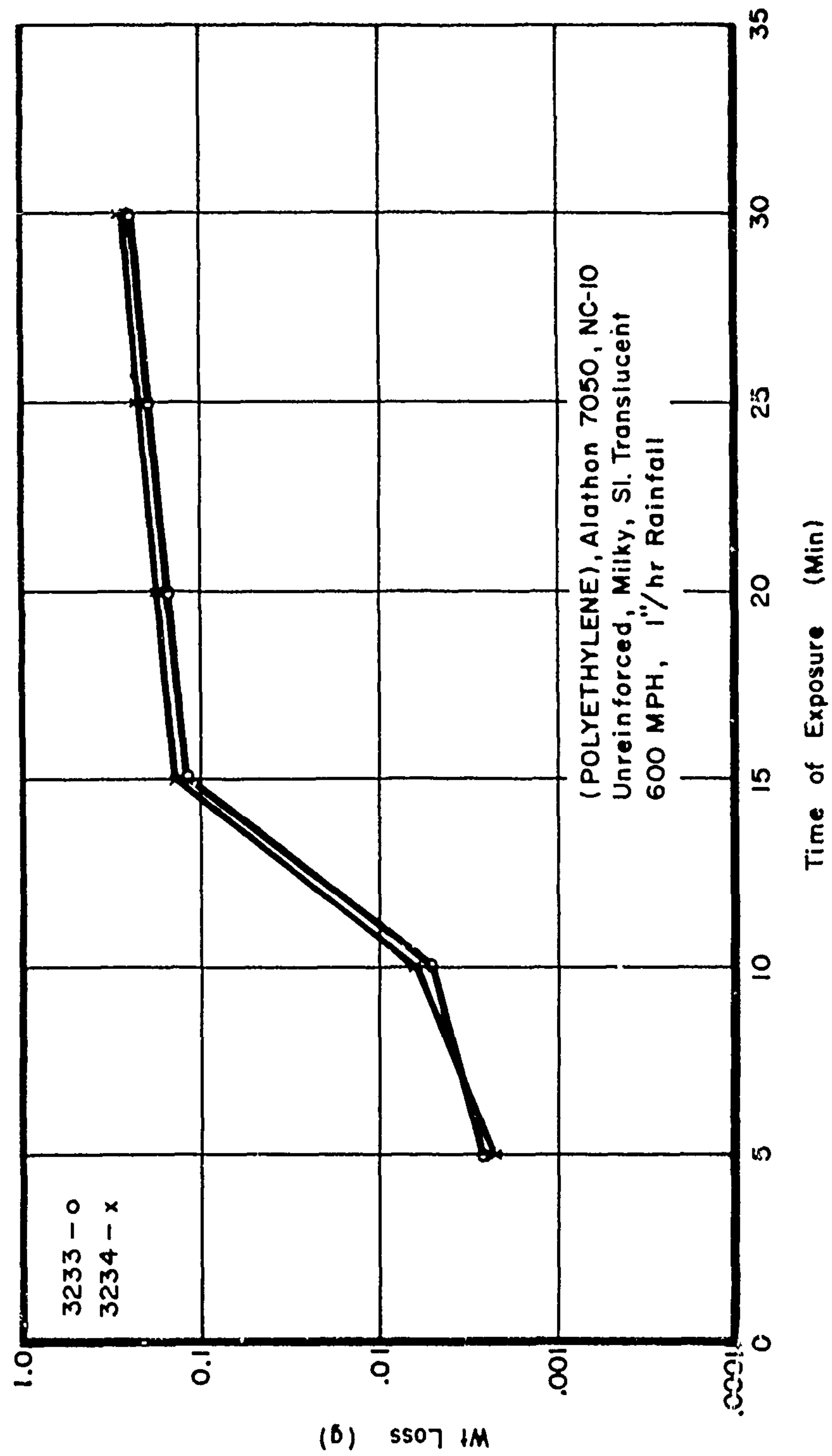

Figure 21. Unreinforced Polyethylene Weight Loss Data (600 MPH) 1 Inch/Hour Rainfall

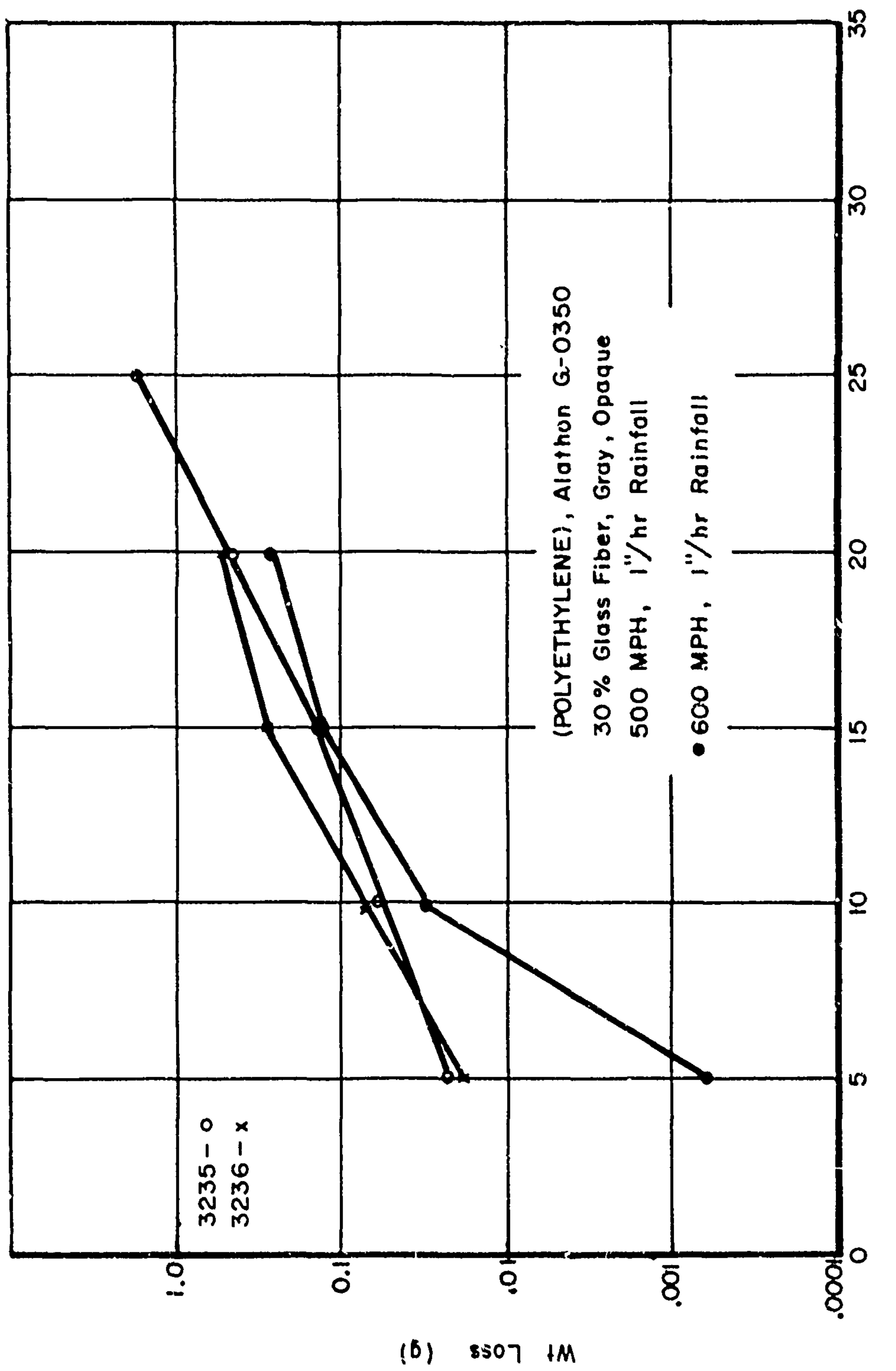

Figure 22. Reinforced Polyethylene Weight Loss Data (500 & 600 MPH) 1 Inch/Hour Rainfall

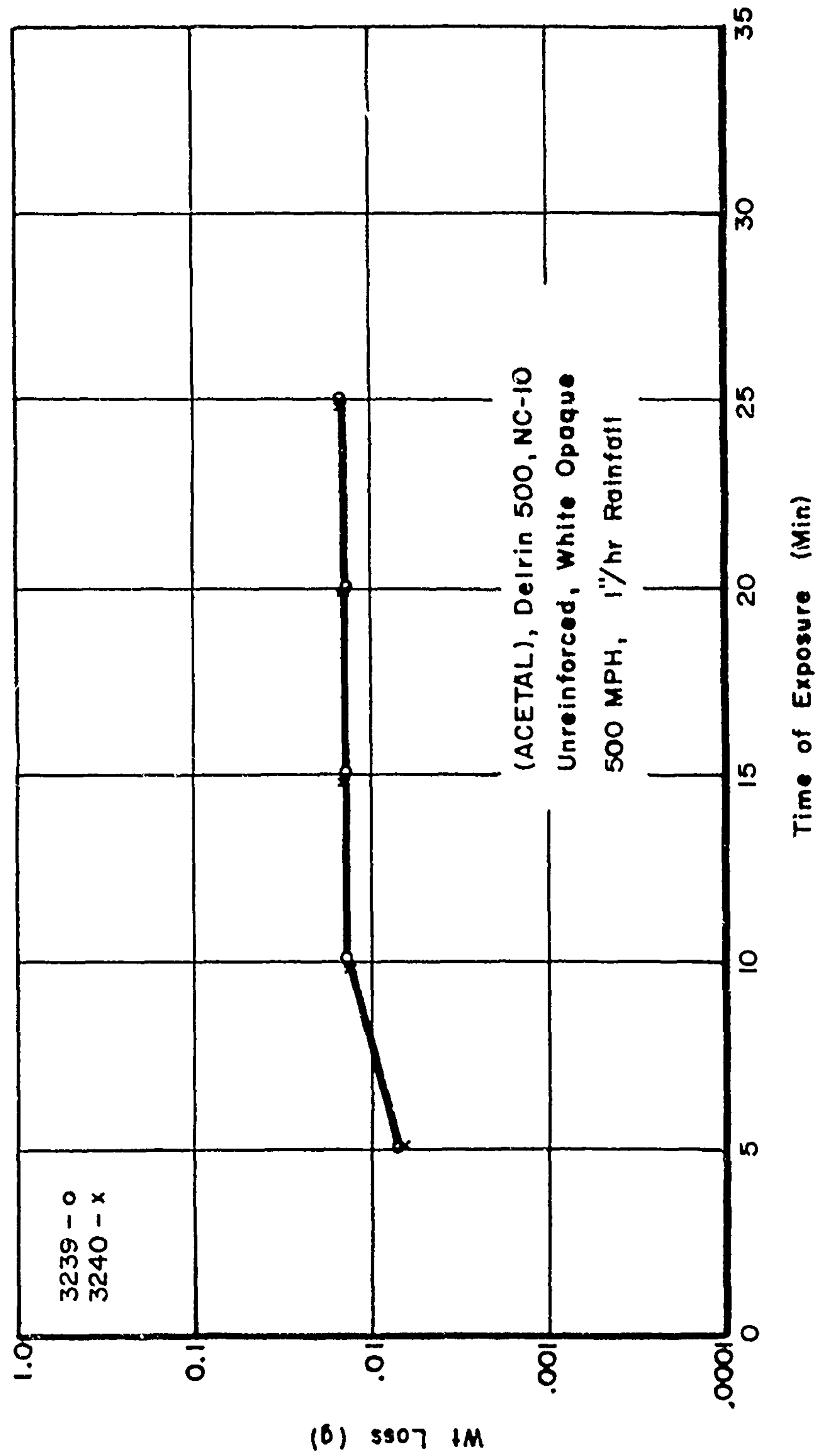

Figure 23. Unreinforced Acetal Weight Loss Data (500 MPH) 1 Inch/Hour Rainfall

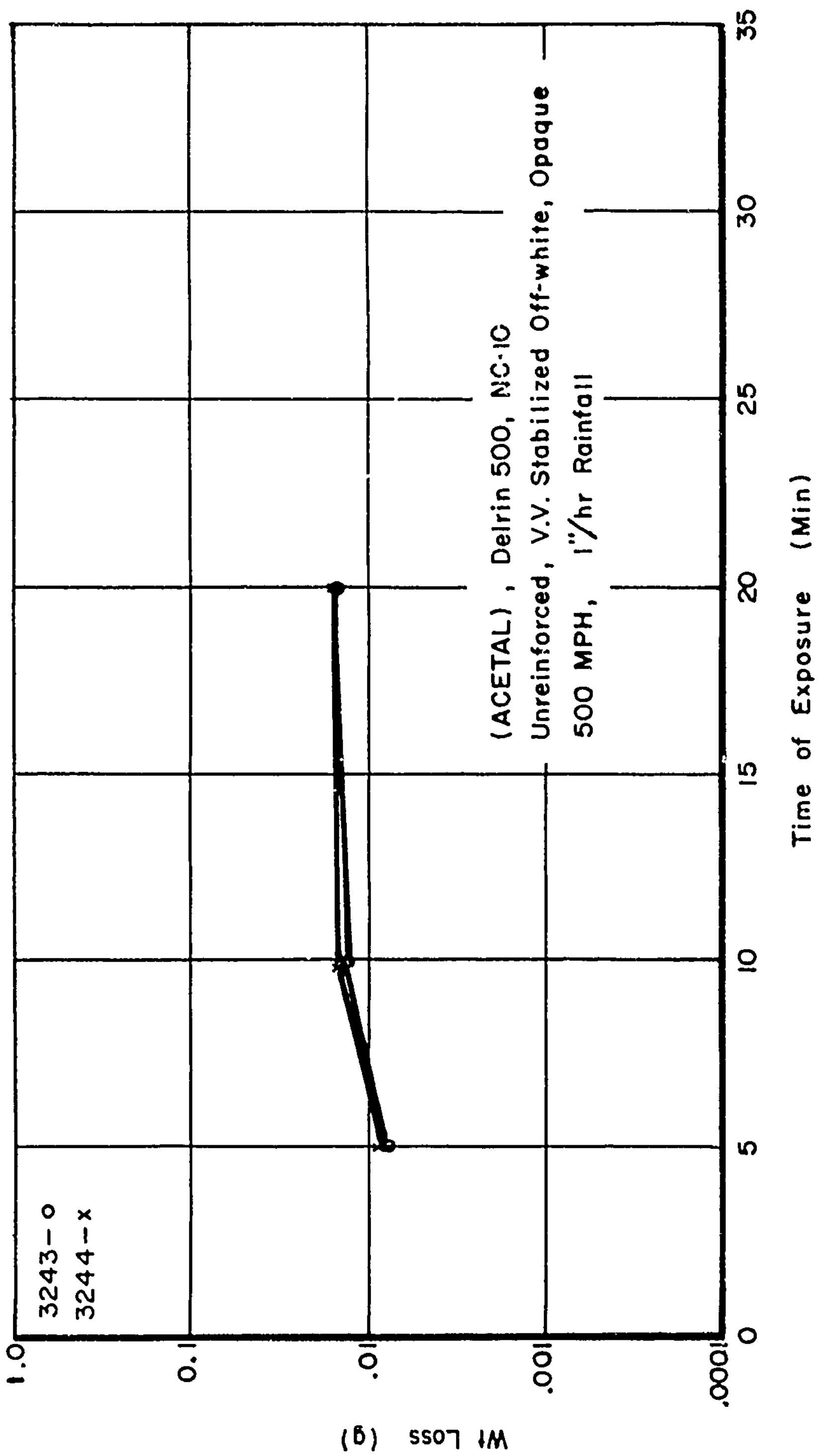

Figure 24. Unreinforced Acetal (U.V. Stabilized) Weight Loss Data (500 MPH) 1 Inch/Hour Rainfall

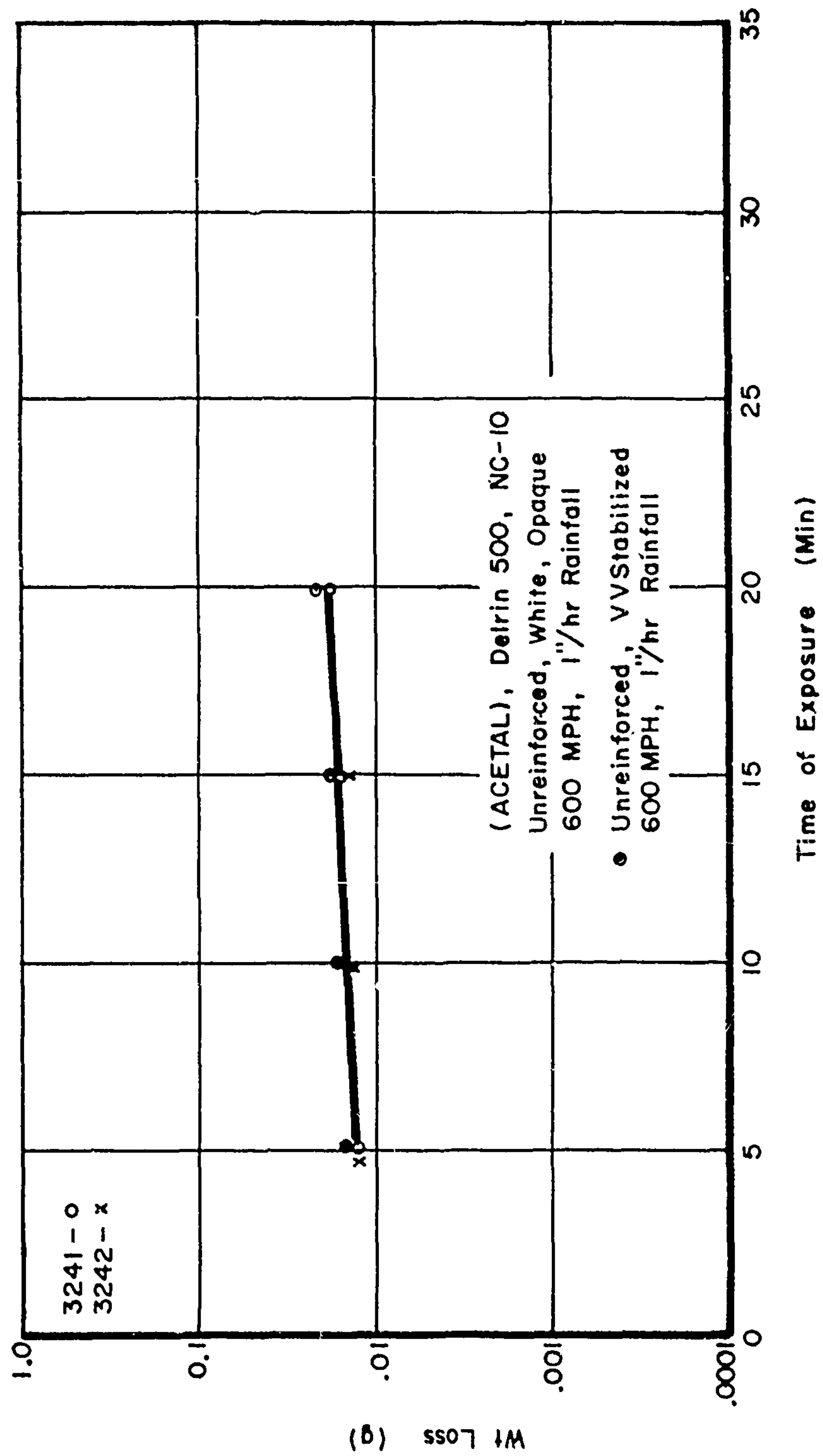

Figure 25. Unreinforced Acetal Weight Loss Data
(600 MPH) 1 Inch/Hour Rainfall

TABLE II

SUMMARY OF RAIN EROSION DATA ON POLYMERIC COATINGS
(500 MPH, 1 INCH/HOUR SIMULATED RAINFALL)

Polymeric Coating	Manufacturer	Thickness (mils)	Substrate	*Average time to failure/min.	Comments
Clear silicone (elastomeric)	Dow, Q92-009	7, 15, 22	Glass-epoxy	0.2-2.9	Erosion failure
Cross-linked polyethylene	Brunswick	15	Glass-epoxy	8.1	Erosion failure
White acrylic	Beech	15	Glass-epoxy	0.3	Erosion failure
Clear, white, black polyester	Presto Chemicals Prestec	12	Glass-epoxy	0.9-2.0	Erosion failure
Polyolefin	G. E. 990	10	Glass-epoxy	7.3	Erosion failure
White polyurethanes (non-elastomeric)	Deft, U. S. Paint Magna Desoto, Finch	12	Glass-epoxy	2.3	Erosion failure
White or black epoxy	Desoto	12	Glass-epoxy	3.5	Erosion failure
White silicone (non-elastomeric)	AFML	12	Glass-epoxy	1.4	Erosion failure
Black neoprene (MIL-C-7439B)	Goodyear 23-56, Gates N-79	8	Glass-epoxy	25.0	Erosion failure
Black neoprene (MIL-C-7439B)	Goodyear 23-56, Gates N-79	12	Glass-epoxy	40.0	Erosion failure
Black polyurethane (MIL-C-83231)	Olin RM115P	12	Glass-epoxy	162.0	Erosion failure
Clear polyurethane (elastomeric)	Olin RM115C	12	Glass-epoxy	180.0	No Damage
White polyurethane (elastomeric)	Olin RM115W	12	Glass-epoxy	100.0	Erosion failure
Carboxy-nitroso rubber	Thiokol	10	Glass-epoxy	9.6	Erosion failure
Flame-sprayed Teflon	duPont 958-201	10	Aluminum	10.0	Erosion failure
Amide-imide	Amoco Chemicals	10	Aluminum	9.9	Erosion failure
Pyrrone	Army Avlabs	10	Glass-epoxy	9.7	Erosion failure
Polysulfone	3M Polymer 360	20	Glass-epoxy	17.0	Erosion failure
Polyphenylene oxide	G. E. 531-801	20	Glass-epoxy	29.1	Erosion failure

TABLE II (CONT'D)

SUMMARY OF RAIN EROSION DATA ON POLYMERIC COATINGS
(500 MPH, 1 INCH/HOUR SIMULATED RAINFALL)

Polymeric Coating	Manufacturer	Thickness (mils)	Substrate	Average time to failure* (hrs)	Comments
Kynar (Polyvinylidene fluoride)	Raychem	10	Glass-epoxy	6.6	Erosion failure
Kel-F (Chlorotrifluoroethylene)	AFML	15	Glass-epoxy	9.6	Erosion failure
Nylon (clear & white)	Pace Co.	6-9	Aluminum	8.5	Erosion failure
Silphenylene-dimethoxysilane	Southern Research	15	Glass-epoxy	24.1	Erosion failure
Ethylene-propylene diene monomer (EPDM)	B. F. Goodrich Nordel 1070	30	Glass-epoxy	38.5	Erosion failure
Epichlorohydrin (Hydrin)	B. F. Goodrich Hydrin 200	30	Glass-epoxy	70.2	Erosion failure
Butyl rubber	AFML	18	Glass-epoxy	3.5	Erosion failure
Nitrile rubber	B. F. Goodrich Hycar XA4810	22	Glass-epoxy	88.0	Erosion failure
Diallyl phthalate	FMC	20	Aluminum	0.9	Erosion failure
Polyphenylene sulfide	Phillips	10	Glass-epoxy	5.8	Erosion failure

* Time for penetration of the coating or loss of adhesion.

See Appendix I for detailed data on these materials.

Glass-epoxy substrates are Epon 828 Epoxy resin (amine-cured) and 181 S glass cloth (A-1100 treated).

Aluminum substrates are 2024-T3.

TABLE III

PHYSICAL PROPERTIES OF ELASTOMERIC COATINGS AND BOOTS

Coating	ASTM D-412 % Elongation at Break	ASTM D-412 Tensile Strength-psi	ASTM D-412 Modulus 100% Elongation psi	* Average Time to Failure (min)	Coating or Boot thickness (mils)
MIL-C-7439B Neoprene	750	1800	50	40.0	12
MIL-C-83231 Polyurethane	700	480	210	162.7	12
Nitrile rubber	440	3100	740	88.0	22
Cross-linked polyethylene	90	1600	125,000	8.1	15
Polysulfone	50-100	10200	360,000	17.0	20
Kel-F (CTFE)	160	4560	200,000	6.6	10
Polyphenylene oxide	50-100	10500	390,000	29.1	20
Pyrrone	2.8	17000	900,000	9.7	10
EPDM	890	3350	200	38.5	30
Hydrin	1180	1750	325	70.2	34

* Glass-epoxy substrates

500 mph, 1 inch/hour simulated rainfall (1.8 mm dia. drop)

TABLE IV

PHYSICAL PROPERTIES AND HARDNESS VS PERFORMANCE OF ELASTOMERIC COATINGS

Coating	ASTM D-412 % Elongation at Break	Tensile strength	100% Modulus psi	Hardness	* Time to Failure (min)
Moisture set, polyether based polyurethane (MIL-C-83231)	700	480	210	Shore A-84	162.7 on glass-epoxy 180.0 no damage on aluminum
Polyether-based polyurethane A	450	4500	1100	Shore A-90	5.0 on glass-epoxy 9.7 on aluminum
Polyether-based polyurethane B	315	8300	3000	Shore D-58	4.8 on glass-epoxy 2.7 on aluminum
Polyether-based polyurethane C	265	8800	3750	Shore D-70	21.1 on glass-epoxy 18.0 on aluminum
Neoprene (MIL-C-7439B)	750	1800	250	Shore A-96	40.0 on glass-epoxy 61.8 on aluminum

* Coatings of 10 - 15 mils thickness

500 MPH, 1 inch/hour simulated rainfall (1.8 mm dia.)

TABLE V

COMPOSITE MATERIALS PROPERTIES

Glass-reinforced Organic Laminates	Porosity-% FTM Std No. 406 MTD 5021	Density-Gm/cc FTM Std No. 406 MTD 5011	Hardness Barcol	Modulus of Elasticity-psi Slope of Tan at Low End of Stress Strain Curve	Shear Strength-psi FTM Std No. 406 MTD 1040	Flexural Strength-psi FTM Std No. 406 MTD 1031	Tensile Strength-psi FTM Std No. 406 MTD 1011	Compressive Strength-psi FTM Std No. 406 MTD 1021	Dielectric Constant (8.6-10.0 KMC) ATC Rept. ARTC 4	Loss Tangent (8.6-10.0 KMC) ATC Rept. ARTC 4
Polybenzimidazole laminate	15	1.65	70	4.75×10^6	6×10^3	11×10^4	87×10^3	7.0×10^3	4.2-4.2	.007
Epon 828 epoxy laminate	0	1.69	50-56	3.08×10^6	6×10^3	58.9×10^3	38.7×10^3	53.7×10^3		
Polyimide laminate		1.51 (Sp. Gr.)	50	2.7×10^6	1500	45×10^3	35×10^3	28×10^3	4.1	.009
Conventional polyimide (Skygard 700) laminate	7.9	1.7	55	2.7×10^6		60×10^3	40×10^3	40×10^3	4.2	.015
DC2106 laminate silicone	0	1.91	73	2.88×10^6		43×10^3	40.6×10^3	22×10^3	4.35	.006 Loss Factor
Dapon M polyester	0	1.82	70			68×10^3	50.5×10^3	49×10^3	4.41	.034
Polyphenylene oxide	0	1.89	57	3.42×10^6		59.8×10^3			4.34	.0175
Low void polyimide	1	1.93	72	3.80×10^6	2.8×10^3	90×10^3			4.48	.007

TABLE VI

INFLUENCE OF VOID CONTENT ON EROSION BEHAVIOR OF COMPOSITES

Composite	Void Content %	Coating	* Time to Failure (min)	Comments
Conventional E glass-polyimide	10	Uncoated	2.0	5 plies eroded
Low void E glass-polyimide	1	Uncoated	4.7	1 ply partially eroded
Conventional E glass-PI	10	0.012" clear polyurethane	9.1	adhesion loss because of substrate breakdown with subsequent erosion failure
Low void E glass-PI	1	0.012" clear polyurethane	52.3	Erosion failure
Conventional E glass-PI	10	0.008" electroplated nickel	21.0	Erosion failure
Conventional E glass-PI	10	0.012" electroplated nickel	180	Erosion failure
Low void E glass-PI	1	0.008" electroplated nickel	180	No damage
Low void E glass-PI	1	0.012" electroplated nickel	180	No damage
High void S glass-epoxy	10	Uncoated	2.0	2 plies eroded
Low void S glass-epoxy	<2	Uncoated	10.0	2 plies eroded
High void S glass-epoxy	10	0.012" neoprene	6-8	Erosion & substrate crushing
Low void S glass-epoxy	<2	0.012" neoprene	40.0	Erosion & substrate crushing
High void S glass-epoxy	10	0.012" polyurethane	21	Small cracks; substrate crushing
Low void S glass-epoxy	<2	0.012" polyurethane	162.7	Erosion failure

* Average value at 500 mph, 1 inch/hour rainfall

TABLE VII

EFFECTS OF CONSTRUCTION: RANDOM CHOPPED FIBERS VS. 2-D CLOTH REINFORCEMENT

Specimen No.	Construction	Matrix Resin	Time of Exposure (min)	Comments
3080	Chopped glass fibers (20% vol)	XPI-MC154 Polyimide	10.0	Chunking on surface (depth of 25 mils)
3081	Chopped glass fibers (20% vol)	XPI-MC154 Polyimide	10.0	Chunking on surface (depth of 25 mils)
3082	Chopped glass fibers (20% vol)	XPI-MC154 Polyimide	20.0	Chunking on surface (depth of 60 mils)
3083	Chopped glass fibers (20% vol)	XPI-MC154 Polyimide	20.0	Chunking on surface (depth of 60 mils)
1685	2-D 181 E glass cloth (69% vol)	BPI373 Polyimide	4.7	Surface mostly intact. partial erosion of 1 ply (9mils)
1686	2-D 181 E glass cloth (69% vol)	BPI373 Polyimide	4.7	Surface mostly intact. partial erosion of 1 ply (9mils)
2878	2-D 181 E glass cloth (69% vol)	BPI373 Polyimide	10.0	Surface mostly intact. partial erosion of 2 plies(18mil)
2879	2-D 181 E glass cloth (69% vol)	BPI373 Polyimide	10.0	Surface mostly intact. partial erosion of 2 plies(18mil)

Note: Void content on all specimens was <2%

Exposures were at 500 MPH, 1 inch/hour rainfall.

TABLE VIII

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to Failure (min)	Comments
1201	Silicone Q92-009	Glass-epoxy	2	500	0.8	Complete erosion
1202	Silicone Q92-009	Glass-epoxy	2		0.8	Complete erosion
1203	Teflon-S (light tan)	Glass-epoxy	10		2.5	Severe surface erosion
1204	Teflon-S (light tan)	Glass-epoxy	20		2.5	Complete Erosion failure
1261	Teflon-"S" (958-201)	Aluminum	10		15.0	Erosion failure
1262	Teflon-"S" (958-201)	Aluminum	10		15.0	Erosion failure
1263	Teflon-"S" (958-201)	Aluminum	10		10.0	Erosion failure
1264	Teflon-"S" (958-201)	Aluminum	10		10.0	Erosion failure
1265	Q92-009 Silicone	Aluminum	7		0.4	Erosion Failure
1266	Q92-009 Silicone	Aluminum	7		0.4	Erosion failure
1267	Q92-009 Silicone	Aluminum	15		1.1	Erosion Failure
1268	Q92-009 Silicone	Aluminum	15		1.1	Erosion failure
1269	Q92-009 Silicone	Aluminum	22		2.9	Erosion Failure
1270	Q92-009 Silicone	Aluminum	22		2.9	Erosion failure
1271	Q92-009 Silicone	Glass-epoxy	7		0.9	Erosion failure
1272	Q92-009 Silicone	Glass-epoxy	7		0.9	Erosion failure
1273	Q92-009 Silicone	Glass-epoxy	15		1.0	Erosion failure
1274	Q92-009 Silicone	Glass-epoxy	15		1.0	Erosion failure
1275	Q92-009 Silicone	Glass-epoxy	22		1.0	Erosion failure
1276	Q92-009 Silicone	Glass-epoxy	22	500	1.0	Erosion failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1291	CD-1154 Black urethane	Aluminum	10	500	64.9	Slight Surface Erosion
1292	CD-1154 Black urethane	Aluminum	10	500	64.9	Erosion failure
1293	CD-1154 Black urethane	Aluminum	10	500	31.6	No Erosion
1294	CD-1154 Black urethane	Aluminum	10	500	31.6	Erosion Failure
1295	CD-1154 Black urethane	Aluminum	10	600	32.7	Erosion Failure
1296	CD-1154 Black urethane	Aluminum	10	600	32.7	Erosion Failure
1297	CD-1154 Black urethane	Epoxy	10	500	23.8	Erosion Failure
1298	CD-1154 Black urethane	Epoxy	10	500	23.8	Erosion Failure
1299	CD-1154 Black urethane	Epoxy	10	500	28.2	Erosion Failure
1300	CD-1154 Black urethane	Epoxy	10	500	28.2	Erosion Failure
1301	CD-1154 Black urethane	Epoxy	10	600	11.0	No Damage
1302	CD-1154 Black urethane	Epoxy	10	600	11.0	Erosion Failure
1303	CD-1154 Black urethane	Epoxy	10	600	7.5	Blistering
1304	CD-1154 Black urethane	Epoxy	10	600	7.5	Erosion Failure
1305	Y-9265 urethane tape	Aluminum	15	500	3.5	Adhesion Failure
1306	Y-9265 urethane tape	Aluminum	15	500	3.5	Adhesion Failure
1307	Y-9265 urethane tape	Aluminum	15	500	3.0	Adhesion Failure
1308	Y-9265 urethane tape	Aluminum	15	500	3.0	No Failure
1309	Y-9265 urethane tape	Aluminum	15	600	2.0	No Damage
1310	Y-9265 urethane tape	Aluminum	15	600	2.0	Adhesion Failure
1311	Y-9265A urethane tape	Aluminum	15	500	58.0	Slight Leading Edge Cracks

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1312	Y-9265A urethane tape	Aluminum	15	500	58.0	Erosion Failure
1313	Y-9265A urethane tape	Aluminum	15	500	42.1	Very slight pitting
1314	Y-9265A urethane tape	Aluminum	15	500	42.1	Slight Erosion
1315	Y-9265A urethane tape	Aluminum	15	600	31.2	Erosion Failure
1316	Y-9265A urethane tape	Aluminum	15	600	31.2	Erosion Failure
1317	Y-9256 urethane tape (Primer)	Aluminum	15	500	44.9	Erosion Failure
1318	Y-9265 urethane tape (Primer)	Aluminum	15	500	44.9	Slight Pitting
1319	Y-9265 urethane tape (Primer)	Aluminum	15	500	42.3	Erosion Failure
1320	Y-9265 urethane tape (Primer)	Aluminum	15	500	42.3	Erosion Failure
1321	Y-9265 urethane tape (Primer)	Aluminum	15	600	26.0	Adhesion Failure
1322	Y-9265 urethane tape (Primer)	Aluminum	15	600	26.0	Adhesion Erosion Failure
1323	HYCAR XA 4810-1 $\left({}^{4003}/{}_{4004}\text{ADH}\right)$	Epoxy	22	500	88.0	Erosion Failure
1324	HYCAR XA 4810-1 $\left({}^{4003}/{}_{4004}\text{ADH}\right)$	Epoxy	22	500	88.0	Slight Erosion & Edge Erosion

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1325	HYCAR XA 4810-1 ($^{4003}/_{4004}$ADH)	Epoxy	22	600	62.8	Erosion Failure
1326	HYCAR XA 4810-1 ($^{4003}/_{4004}$ADH)	Epoxy	22	600	62.8	Erosion Failure
1327	HYCAR XA 4810-1 ($^{4003}/_{4004}$ADH)	Aluminum	22	500	52.1	Erosion Failure
1328	HYCAR XA 4810-1 ($^{4003}/_{4004}$ADH)	Aluminum	22	500	52.1	Slight Erosion
1329	ESTANE XA-4810-2 ($^{7087}/_{7074}$ADH)	Epoxy	18	500	30.6	No Erosion
1330	ESTANE XA-4810-2 ($^{7087}/_{7074}$ADH)	Epoxy	18	500	30.6	Edge Erosion
1331	ESTANE XA-4810-2 ($^{7087}/_{7074}$ADH)	Epoxy	18	600	11.4	Slight surface damage
1332	ESTANE XA-4810-2 ($^{7087}/_{7074}$ADH)	Epoxy	18	600	11.4	Erosion (Bad spot in coating)
1333	ESTANE XA-4810-2 ($^{7087}/_{7074}$ADH)	Aluminum	18	500	84.3	Erosion Failure
1334	ESTANE XA-4810-2 ($^{7087}/_{7074}$ADH)	Aluminum	18	500	84.3	Slight Erosion

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mil)	Velocity MPH	Time to failure (min)	Comments
1335	Black neoprene XA48103 (R-35ADH)	Epoxy	22	500	43.8	Surface Erosion
1336	Black neoprene XA48103 (R-35ADH)	Epoxy	22	500	43.8	Erosion Failure-inboard
1337	Black neoprene XA48103 (R-35ADH)	Epoxy	22	600	23.3	Surface erosion (pitting)
1338	Black neoprene XA48103 (R-35ADH)	Epoxy	22	600	23.3	Erosion failure (tear and pitting)
1339	Black neoprene XA48103 (R-35ADH)	Aluminum	22	500	117.0	Erosion Failure
1340	Black neoprene XA48103 (R-35ADH)	Aluminum	22	500	117.0	Erosion Failure
1341	White neoprene XA4810-4 (EC1300L)	Epoxy	24	500	60.0	Erosion Failure
1342	White neoprene XA4810-4 (EC1300L)	Epoxy	24	500	60.0	Erosion Failure
1343	White neoprene XA4810-4 (EC1300L)	Epoxy	24	600	15.6	Erosion Failure due to edge release
1344	White neoprene XA4810-4 (EC1300L)	Epoxy	24	600	15.6	No Damage
1345	White neoprene XA4810-4 (EC1300L)	Aluminum	24	500	87.3	Erosion Failure
1346	White neoprene XA4810-4 (EC1300L)	Aluminum	24	500	87.3	Severe Pitting

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1347	C-141 XA4810-5 Neoprene boot (R-35)	Epoxy	24	500	First layer 51.5 Second layer 57.0	63.0 Min.
1348	C-141 XA4810-5 Neoprene boot (R-35)	Epoxy	24	500	First layer 56.3 Second layer 63.0	
1349	C-141 XA4810-5 Neoprene boot (R-35)	Epoxy	24	600	7.8	Erosion Failure
1350	C-141 XA4810-5 Neoprene boot (R-35)	Epoxy	24	600	7.8	Surface Damage Only
1351	C-141 XA4810-5 Neoprene boot (R-35)	Aluminum	24	500	First layer 51.4	
1352	C-141 XA4810-5 Neoprene boot (R-35)	Aluminum	24	500	First layer 36.9 Second layer 51.4	51.4 Min.
1353	C-141 XA4810-6 Neoprene/Rubber ply (R-35)	Epoxy	24	500	First layer 43.2 Second layer 61.0	61.0 Min.
1354	C-141 XA4810-6 Neoprene/Rubber ply (R-35)	Epoxy	24	500	Surface cracks only	
1355	C-141 XA4810-6 Neoprene/Rubber ply (R-35)	Epoxy	24	600	First layer 11.6	Surface cracks
1356	C-141 XA4810-6 Neoprene/Rubber ply (R-35)	Epoxy	24	600	Second layer 14.1	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1357	C-141 XA4810-6 Neoprene/rubber ply (R-35)	Aluminum	24	500	First layer 20.7	37.5 Min.
1358	C-141 XA4810-6 Neoprene/rubber ply (R-35)	Aluminum	24	500	Second layer 37.5	
1359	SM-466 ⊥ Oriented Glass-epoxy	Comp.	—	500	18.1	Erosion Failure
1360	SM-466 ⊥ Oriented Glass-epoxy	Comp.	—	500	18.1	Erosion Failure
1361	Carboxy-Nitroso rubber (ADH B)	Aluminum	10	500	1.3	Adhesion Failure
1362	Carboxy-Nitroso rubber (ADH B)	Aluminum	10	500	1.3	No Erosion
1363	10% CNR Coatings	Aluminum	10	500	2.1	Adhesion Failure
1364	10% CNR Coatings	Aluminum	10	500	2.1	No Erosion
1365	10% CNR Coating/ ADH B (2 coats)	Aluminum	10	500	3.7	Adhesion Failure
1366	10% CNR Coating/ ADH B (2 coats)	Aluminum	10	500	3.7	Adhesion Failure
1367	Olin Rm-115 Urethane (uncat)	Aluminum	15	500	152.0	Erosion Failure
1368	Olin Rm-115 Urethane (uncat)	Aluminum	15	500	152.0	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1369	Olin Rm115 Urethane (uncat)	Epoxy	15	500	69.9	Erosion Failure
1370	Olin Rm115 Urethane (uncat)	Epoxy	15	500	69.9	Erosion Failure
1371	Olin Rm115 Urethane (cat)	Epoxy	15	500	111.0	
						Inboarded Edge Erosion
1372	Olin Rm115 Urethane (cat)	Epoxy	15	500	111.0	
1373	Olin Rm115 Urethane (cat)	Aluminum	15	500	169.1	Erosion Failure
1374	Olin Rm115 Urethane (cat)	Aluminum	15	500	169.1	Edge Erosion
1375	Goodyear Black Neoprene	Epoxy	12	500	160.8	Erosion Failure
1376	Goodyear Black Neoprene	Epoxy	12	500	160.8	Slight Erosion
1377	Goodyear Black Neoprene	Aluminum	12	500	88.7	Erosion Failure
1378	Goodyear Black Neoprene	Aluminum	12	500	88.7	Blistering & Surface Damage
1379	Cross linked Polyethylene	Aluminum	15	500	21.1	Erosion Failure
1380	Cross linked Polyethylene	Aluminum	15	500	21.1	Leading Edge Erosion

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mil)	Velocity MPH	Time to failure (min)	Comments
1381	Cross linked Polyethylene	Epoxy	15	500	8.1	Very Slight Erosion L. E.
1382	Cross linked Polyethylene	Epoxy	15	500	8.1	Erosion Failure
1383	Polysulfone	Epoxy	20	500	17.0	Slight Surface roughning
1384	Polysulfone	Epoxy	20	500	17.0	Erosion Failure
1385	Polysulfone	Aluminum	20	500	1.7	Erosion Failure
1386	Polysulfone	Aluminum	20	500	1.7	Adhesion Starting to go
1387	Polymer 360	Aluminum	15	500	7.2	Erosion Failure?
1388	Polymer 360	Aluminum	15	500	7.2	No Damage
1389	Polymer 360	Epoxy	15	500	8.6	Erosion Failure ?
1390	Polymer 360	Epoxy	15	500	8.6	No Damage
1391	Polyphenylene oxide	Glass laminate E-181		500	3.1	Erosion Failure
1391	Polyphenylene oxide	Glass laminate E-181		500	3.1	Erosion Failure
1392	Polyphenylene oxide	Glass laminate E-181		500	3.1	Erosion Failure
1393	Polyphenylene oxide	Glass laminate E-181		500	4.0	Erosion Failure
1394	Polyphenylene oxide	Glass laminate E-181		500	4.0	Erosion Failure
1395	CTFE Fluorocarbon	Polyimide	15	500	9.1	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1396	CTFE Fluorocarbon	Polyimide	15	500	9.1	Surface Erosion
1397	HIFAX 1900 High Mol. Wt. polyethylene	Epoxy	15		32.7	Blistering & Erosion Failure
1398	HIFAX 1900 High Mol. Wt. polyethylene	Epoxy	15		32.7	Blistering & Erosion Failure
1399	HIFAX 1900 High Mol. Wt. polyethylene	Epoxy	15		24.5	Roughing of the surface
1400	HIFAX 1900 High Mol. Wt. polyethylene	Epoxy	15		24.5	Erosion Failure
1401	PPO 531-801 (Commercial grade)	Aluminum	20		4.0	Erosion Failure
1402	PPO 531-801 (Commercial grade)	Aluminum	20		4.0	Erosion Failure
1403	PPO 531-801 (Commercial grade)	Epoxy	20		29.1	Slight Abrasion
1404	PPO 531-801 (Commercial grade)	Epoxy	20		29.1	Erosion Failure
1405	PPO 681-111 (Electrical grade)	Epoxy	20		12.4	Erosion Failure
1406	PPO 681-111 (Electrical grade)	Epoxy	20		12.4	Erosion Failure
1407	PPO 681-111 (Electrical grade)	Aluminum	20		2.5	Erosion Failure
1408	PPO 681-111 (Electrical grade)	Aluminum	20	500	2.5	Slight Adhesion failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1415	⊥ oriented glass-epoxy comp. SM-492		—	500	30.0	Erosion Failure
1416	⊥ oriented glass-epoxy comp. SM-492		—		30.0	Erosion Failure
1417	Preformed Genthane Polyurethane	Aluminum	15		66.2	Erosion Failure
1418	Preformed Genthane Polyurethane	Aluminum	15		66.2	Erosion Failure
1467	DIALLYL Phthalate molded				20.0	Erosion Failure
1468	DIALLYL Phthalate molded				20.0	Erosion Failure
1469	DIALLYL Phthalate molded				20.0	Erosion Failure
1470	DIALLYL Phthalate molded				20.0	Erosion Failure
1471	DIALLYL Phthalate w/carbon				20.0	Erosion Failure
1472	DIALLYL Phthalate w/carbon				20.0	Erosion Failure
1473	DIALLYL Phthalate w/carbon				20.0	Erosion Failure
1474	DIALLYL Phthalate w/carbon			500	20.0	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1475	20 mil Dap sheet + Fiberglass			500	10.4	Erosion leading edge to lam.
1476	20 mil Dap sheet + Fiberglass				10.4	Erosion & Chipping
1477	20 Mil Dap over molded dap + glass				10.5	Erosion Failure } Couldn't see coating erode
1478	20 mil Dap over molded dap + glass				10.5	Erosion Failure }
1479	20 mil Dap over molded dap + glass				1.5	Erosion Failure
1480	20 mil Dap over molded Dap + glass				1.5	Erosion Failure
1481	20 mil Dap over Aluminum				0.9	Erosion Failure
1482	20 mil Dap over Aluminum				0.9	Erosion Failure
1597	CF127B Kynar	Epoxy	4		1.5	No Failure
1598	CF127B Kynar	Epoxy	4		1.5	Erosion Failure
1599	CF127B Kynar	Epoxy	10		6.6	Erosion Failure
1600	CF127B Kynar	Epoxy	10		6.6	Erosion Failure
1617	BTDA-Pyrrone	Aluminum	(8-10)		9.7	Slight Erosion
1618	BTDA-Pyrrone	Aluminum	(8-10)		9.7	Erosion Failure
1673	Rm115 (Type I)	Low void polyimide	12	500	52.3	No Damage

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1674	Rm115 Polyurethane	Low Void Polyimide	12	500	52.3	Erosion Failure
1675	Rm115 Type II	Low Void Polyimide	14		180.0	Edge Erosion at 120.0 Side edge 170.0 Reading edge
1676	Rm115 Type II	Low Void Polyimide	14		180.0	No Damage
1677	Rm115 Type I	Conventional Polyimide	12		9.1	Adhesion then Erosion Failure
1678	Rm115 Type I	Conventional Polyimide	12		9.1	Beginning Adhesion Damage
1679	Rm115 Type II	Conventional Polyimide	14		5.5	Beginning Adhesion Damage
1680	Rm115 Type II	Conventional Polyimide	14		5.5	Adhesion then Erosion Failure
1681	White Polyurethane	Epoxy	10		2.3	Erosion Failure
1682	White Polyurethane	Epoxy	10		2.3	Erosion Failure
1683	White Polyurethane	Epoxy	10		2.8	Erosion Failure
1684	White Polyurethane	Epoxy	10		2.8	Slight Erosion
1685	Low Void Polyimide	Laminates	—		4.7	Erosion Failure
1686	Low Void Polyimide	Laminates	—		4.7	Erosion Failure
1687	Conventional Polyimide	Laminates	—		2.0	Erosion Failure
1688	Conventional Polyimide	Laminates	—		2.0	Erosion Failure
1689	Graphite —	Epoxy	—	500	1.0	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1690	Graphite —	Epoxy	—	500	1.0	Erosion Failure
1691	Boron —	Epoxy	—		2.0	Erosion Failure
1692	Boron —	Epoxy	—		2.0	Erosion Failure
1693	Plexiglas (bulk)		—		6.0	Surface Erosion
1694	Plexiglas (bulk)		—		6.0	Surface Erosion
1699	MIL-C-7439B neoprene II	Epoxy	12		69.8	Erosion Failure
1700	MIL-C-7439B neoprene II	Epoxy	12		69.8	Erosion Failure
1701	MIL-C-7439B neoprene II	Epoxy	12		54.6	Surface Erosion
1702	MIL-C-7439B neoprene II	Epoxy	12		54.6	Erosion Failure
1703	MIL-C-7439B neoprene II	Epoxy	12		48.8	Erosion Failure
1704	MIL-C-7439B neoprene II	Epoxy	12		48.8	Surface Erosion
1705	MIL-C-7439B neoprene I	Epoxy	12		17.7	Surface Pitting
1706	MIL-C-7439B neoprene I	Epoxy	12		17.7	Erosion Failure
1707	MIL-C-7439B neoprene I	Epoxy	12	500	20.8	Surface Erosion

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1708	MIL-C-7439B neoprene I	Epoxy	12	500	20.8	Erosion Failure
1709	MIL-C-7439B neoprene I	Epoxy	12		13.7	Erosion Failure
1710	MIL-C-7439B neoprene I	Epoxy	12		13.7	specimen parbially damaged initially. Surface Pitting
1711	MIL-C-83231 Polyurethane II	Epoxy	12		140.0	Erosion Failure
1712	MIL-C-83231 Polyurethane II	Epoxy	12		140.0	Erosion Failure
1713	MIL-C-83231 Polyurethane II	Epoxy	12		111.2	No Erosion
1714	MIL-C-83231 Polyurethane II	Epoxy	12		111.2	Erosion failure
1721	MIL-C-83231 Polyurethane I	Epoxy	12		180.0	Erosion Failure
1722	MIL-C-83231 Polyurethane I	Epoxy	12		180.0	Erosion failure
1761	Y-9265 Urethane Tape	Aluminum	15		53.5	Erosion Failure
1762	Y-9265 Urethane Tape	Aluminum	15		53.5	Slight Cracking
1763	Y-9265 Urethane Tape	Epoxy	15	500	62.5	Adhesion-Erosion

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness(mils)	Velocity MPH	Time to failure (min)	Comments
1764	Y-9265 urethane Tape 15 mils	Epoxy	15	500	62.5	Adhesion - Erosion
1765	White Acrylic/Y9265 Tape	Aluminum	17		0.3	white tape 33.4 adhesion - erosion - Erosion Failure
1766	White Acrylic/Y9265 Tape	Aluminum	17		0.3	white tape 33.4 adhesion erosion Erosion Failure
1767	White Acrylic/Y9265 Tape	Epoxy	17		0.3, 57.0	Adhesion Failure Erosion Failure
1815	Jeff. Chem Epoxy	Epoxy	6		5.2	Erosion Failure
1816	Jeff. Chem Epoxy	Epoxy	6		5.2	Erosion Failure
1817	Jeff. Chem Epoxy	Epoxy	6		3.1	Erosion Failure
1818	Jeff. Chem Epoxy	Epoxy	6		3.1	No Failure
1819	Jeff. Chem Epoxy	Epoxy	6		3.5	Erosion Failure
1820	Jeff. Chem Epoxy	Epoxy	6		3.5	Erosion Failure
1821	Poly olefin 990	Epoxy	10		6.3	Adhesion (2 min) Erosion
1822	Poly olefin 990	Epoxy	10		6.3	Adhesion (2 min) Erosion
1823	Poly olefin 990	Epoxy	10		7.3	Adhesion (2 min) Erosion approx.
1824	Poly olefin 990	Epoxy	10		7.3	Adhesion (2 min)
1825	Y-9265 Urethane tape	Epoxy	15		40.0	Slight Adhesion Loss
1826	Y-9265 Urethane tape	Epoxy	15	500	40.0	Adhesion-Erosion

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mil.)	Velocity MPH	Time to failure (min)	Comments
1851	Prestec clear polyester 3081 primer	Epoxy	16	500	2.0	Erosion Failure
1852	Prestec clear polyester 3081 primer	Epoxy	16		2.0	Erosion Failure
1853	Prestec clear polyester 3081 primer	Epoxy	16		2.0	Erosion Failure
1854	Prestec clear polyester 3081 primer	Epoxy	16		2.0	Erosion Failure
1855	Prestec Black polyester 3081 primer	Epoxy	13		0.9	Slight Erosion
1856	Prestec Black 3081 primer	Epoxy	13		0.9	Severe Erosion
1857	Prestec Black 3081 primer	Epoxy	13		0.7	Erosion Failure
1858	Prestec Black 3081 primer	Epoxy	13		0.7	Erosion Failure
1859	Prestec White polyester 3081 primer	Epoxy	14		1.5	Slight Erosion
1860	Prestec White polyester 3081 primer	Epoxy	14		1.5	Erosion Failure
1861	Prestec White polyester 3081 primer	Epoxy	14		1.3	No Damage
1862	Prestec White polyester 3081 primer	Epoxy	14		1.3	Erosion Failure
1863	Neoprene Gates II	828 Epoxy	12	500	50.7	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1864	Neoprene Gates II	828 Epoxy	12	500	50.7	Erosion Failure
1865	Neoprene Gates II	828 Epoxy	12		44.5	Erosion Failure
1866	Neoprene Gates II	828 Epoxy	12		44.5	Severe Surface damage
1887	Rm115P, type I	Epoxy	12		239.9	Erosion Failure
1888	Rm115P, type I	Epoxy	12		239.9	No Failure
1889	Rm115P, type I	Epoxy	12		50.0	No Failure
1890	Rm115P, type I	Epoxy	12		50.0	Erosion Failure
1891	Rm115P, type I	Epoxy	12		41.5	No Failure
1892	Rm115P, type I	Epoxy	12		41.5	Erosion Failure
1893	Rm115AS type II	Epoxy	12		42.6	No Failure
1894	Rm115AS type II	Epoxy	12		42.6	Erosion Failure
1895	Rm115AS type II	Epoxy	12		73.0	Erosion Failure
1896	Rm115AS type II	Epoxy	12		73.0	No Failure
1897	Rm115AS type II	Epoxy	12		305.8	No Damage
1898	Rm115AS type II	Epoxy	12		305.8	Erosion Failure
1899	Sprayed Teflon	Aluminum	5		1.9	Erosion Failure
1900	Sprayed Teflon	Aluminum	5		1.9	Erosion Failure
1901	Sprayed Teflon	Aluminum	5		2.5	Erosion Failure
1902	Sprayed Teflon	Aluminum	5		2.5	Erosion Failure
1903	Sprayed Teflon	Epoxy	5	500	1.8	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1904	Sprayed Teflon	Epoxy	5	500	1.8	Erosion Failure
1905	Sprayed Teflon	Epoxy	5		1.8	Erosion Failure
1906	Sprayed Teflon	Epoxy	5		1.8	Erosion Failure
1912	Carboxy-Nitroso rubber	Epoxy	10		9.3	No Damage
1913	Carboxy-Nitroso rubber	Epoxy	10		9.3	Inboard Failure
1914	Carboxy-Nitroso rubber	Epoxy	10		9.9	No Damage
1915	Carboxy-Nitroso rubber	Epoxy	10	500	9.9	Erosion Failure
1916	Carboxy-Nitroso rubber	Epoxy	10	600	3.8	Erosion Failure
1917	Carboxy-Nitroso rubber	Epoxy	10	600	3.8	Erosion Failure
1918	Carboxy-Nitroso rubber	Aluminum	10	500	8.5	No Damage
1919	Carboxy-Nitroso rubber	Aluminum	10	500	8.5	Erosion Adhesion failure
1920	Carboxy-Nitroso rubber	Aluminum	10	500	8.7	No Damage
1921	Carboxy-Nitroso rubber	Aluminum	10	500	8.7	Erosion Adhesion failure
1922	Carboxy-Nitroso rubber	Aluminum	10	600	0.8	Adhesion Loss

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
1923	Carboxy-Nitroso rubber	Aluminum	10	600	0.8	No Damage
2049	White Silicone	Epoxy	12	500	1.4	Erosion Failure
2050	White Silicone	Epoxy	12	500	1.4	Erosion Failure
2051	White Silicone	Epoxy	12	500	1.2	Erosion Failure
2052	White Silicone	Epoxy	12	500	1.2	Erosion Failure
2059	Amide-Imide	Aluminum	10	500	10.5	Erosion Failure
2060	Amide-Imide	Aluminum	10	500	10.5	No Damage
2061	Amide-Imide	Aluminum	10	500	7.3	Erosion Failure
2062	Amide-Imide	Aluminum	10	500	7.3	No Damage
2117	Magna White Polyurethane	Epoxy	12	500	1.9	Erosion Failure
2118	Magna White Polyurethane	Epoxy	12	500	1.9	No Damage
2119	Magna White Polyurethane	Epoxy	12	500	18.4	No Damage
2120	Magna White Polyurethane	Epoxy	12	500	18.4	Erosion Failure
2121	Magna black polyurethane	Epoxy	12	500	0.9	Erosion Failure
2122	Magna black polyurethane	Epoxy	12	500	0.9	No Damage

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
2125	Cross linked Poly-ethylene	Epoxy	10	500	1.0	Slight surface erosion
2126	Cross linked Poly-ethylene	Epoxy	10		1.0	Erosion at a defective spot on leading edge before run
2127	Cross linked Poly-ethylene	Epoxy	10		3.8	Adhesion Surface Erosion End Caps.
2128	Cross linked Poly-ethylene	Epoxy	10		3.8	Adhesion Erosion End Caps.
2129	Cross linked Poly-ethylene	Epoxy	20		14.7	Adhesion-Surface Erosion
2130	Cross linked Poly-ethylene	Epoxy	20		14.7	Adhesion-Erosion
2131	Cross linked Poly-ethylene	Epoxy	20		12.6	Adhesion-Erosion
2132	Cross linked Poly-ethylene	Epoxy	20		12.6	Adhesion-Surface erosion
2133	Cross linked Poly-ethylene	Epoxy	30		67.1	Surface Erosion
2134	Cross linked Poly-ethylene	Epoxy	30		67.1	Adhesion-Erosion
2135	Cross linked Poly-ethylene	Epoxy	30		49.1	Surface Erosion
2136	Cross linked Poly-ethylene	Epoxy	30	500	49.1	Adhesion-Erosion

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
2137	Butyl Rubber	Epoxy	18	500	3.5	Adhesion Erosion
2138	Butyl Rubber	Epoxy	18		3.5	Surface Erosion
2139	Kel-F	Epoxy	15		9.6	Erosion Failure
2140	Kel-F	Epoxy	15		9.6	Erosion Failure
2199	Desoto Urethane (Aliphatic)	Epoxy	4.5		1.3	One spot eroded
2200	Desoto Urethane (Aliphatic)	Epoxy	4.5		1.3	Erosion Failure
2201	Desoto Urethane (Aliphatic)	Aluminum	11		9.4	Adhesion Failure
2202	Desoto Urethane (Aliphatic)	Aluminum	11		9.4	Adhesion Failure
2203	Desoto Urethane (Aliphatic)	Aluminum	11		8.9	Slight Flow of Coating
2204	Desoto Urethane (Aliphatic)	Aluminum	11		8.9	Adhesion Failure
2205	Finch Urethane	Aluminum	3.0		3.8	Slight Erosion
2206	Finch Urethane	Aluminum	3.0		3.8	Erosion Failure
2207	Finch Urethane	Aluminum	3.0		3.4	Erosion Failure
2208	Finch Urethane	Aluminum	3.0		3.4	Erosion Failure
2209	US Paint Urethane	Epoxy	3.0		1.3	Erosion Failure
2210	US Paint Urethane	Epoxy	3.0		1.3	Erosion Failure
2211	US Paint Urethane	Epoxy	3.0	500	1.3	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
2212	US Paint Urethane	Epoxy	3.0	500	1.3	Erosion Failure
2213	US Paint Urethane	Aluminum	3.0		3.2	Erosion Failure
2214	US Paint Urethane	Aluminum	3.0	↑	3.2	Erosion Failure
2215	US Paint Urethane	Aluminum	3.0		2.4	Erosion Failure
2216	US Paint Urethane	Aluminum	3.0		2.4	Erosion Failure
2217	Neoprene Ray-Chem	Epoxy	16-22		61.6	Erosion Failure
2218	Neoprene Ray-Chem	Epoxy	16-22		61.6	Slight Erosion
2219	Neoprene Ray-Chem	Epoxy	16-22		52.0	Erosion Failure
2220	Neoprene Ray-Chem	Epoxy	16-22		52.0	Erosion Failure
2221	RNF-100 Polyolefin Ray-Chem	Epoxy	15-20		23.8	Slight Erosion
2222	RNF-100 Polyolefin Ray-Chem	Epoxy	15-20		23.8	Erosion Failure
2223	Viton Ray-Chem	Epoxy	36-41		Not run	Too Thick
2224	Viton Ray-Chem	Epoxy	36-41		Not run	
2225	KYNAR Ray-Chem	Epoxy	11-13		17.2	Erosion Failure
2226	KYNAR Ray-Chem	Epoxy	11-13		17.2	Erosion Failure
2227	RNF-100 Translucent Ray Chem	Epoxy	16-23		Not run	No Matching specimen
2228	Neoprene boot, laminated (Goodyear)	Epoxy	25-26	↓	29.2	Erosion Failure
2229	Neoprene boot, laminated (Goodyear)	Epoxy	25-26	500	29.2	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
2230	Neoprene boot, laminated (Goodyear)	Epoxy	25-26	500	24.0	Erosion Failure
2231	Neoprene boot, laminated (Goodyear)	Epoxy	25-26		24.0	Erosion Failure
2232	Neoprene boot, laminated (Goodyear)	Epoxy	25-26		27.5	Erosion Failure
2233	Neoprene boot, laminated (Goodyear)	Epoxy	25-26		27.5	Erosion Failure
2246	⊥ oriented glass epoxy (uncoated)		--		15.0	Erosion on back edges
2247	⊥ oriented glass epoxy (uncoated)		--		5.0	Erosion on back edges
2248	RM115 T-1 urethane	⊥ oriented glass-epoxy	12		58.9	Erosion Failure
2249	RM115 T-1 urethane	⊥ oriented glass-epoxy	12		58.9	Erosion Failure
2250	Quartz-polyimide	(uncoated)	--		4.2	Erosion Failure
2251	Quartz-polyimide	(uncoated)	--		4.2	Erosion Failure
2252	RM115 T-1 urethane	Quartz polyimide	12		58.2	Erosion Failure
2253	RM115 T-1 urethane	Quartz polyimide	12		58.2	Erosion Failure
2279	Deft urethane system	Aluminum	2.5	500	6.5	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to Failure (min)	Comments
2280	Deft urethane system	Aluminum	2.5	500	6.5	Erosion Failure
2281	Deft urethane system	Aluminum	2.5		6.0	Erosion Failure
2282	Deft urethane system	Aluminum	2.5		6.0	Erosion Failure
2283	Desoto Flex, urethane	Aluminum	10		17.3	Erosion of both layers
2284	Desoto Flex, urethane	Aluminum	10		17.3	Erosion of first layer only
2285	Desoto Flex, urethane	Aluminum	10		19.6	Erosion both layer
2286	Desoto Flex, urethane	Aluminum	10		19.6	Erosion both layers
2287	Olin RM115 white urethane	Aluminum	7		31.4	Erosion Failure
2288	Olin RM115 white urethane	Aluminum	7		31.4	Erosion Failure
2289	Olin RM115 white urethane	Aluminum	7		45.3	Erosion Failure (slight)
2290	Olin RM115 white urethane	Aluminum	7		45.3	Erosion Failure
2291	Olin RM115 with Add'l Topcoats 11.2 mil	Aluminum	10.5	500	85.0	Slight Erosion

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
2292	Olin Rm115 with Add'l Topcoats 11.2 mil	Aluminum	10.5	500	85.0	Slight Erosion
2293	Olin Rm115 with Add'l Topcoat 11.2 mil	Aluminum	10.5		88.5	No Damage
2294	Olin Rm115 Add'l Topcoat 11.2 mil	Aluminum	10.5		88.8	Erosion Failure
2295	PACECO Nylon clear 900	Aluminum	9		6.6	Erosion Failure
2296	PACECO Nylon clear 900	Aluminum	9		6.6	Erosion Failure
2297	PACECO Nylon clear 900	Aluminum	9		6.7	Erosion Failure
2298	PACECO Nylon clear 900	Aluminum	9		6.7	Erosion Failure
2299	PACECO Nylon white 902	Aluminum	6		8.5	Erosion Failure
2300	PACECO Nylon white 902	Aluminum	6		8.5	No Failure
2301	PACECO Nylon white 902	Aluminum	6		8.4	No Failure
2302	PACECO Nylon white 902	Aluminum	6	500	8.4	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (Mil)	Velocity MPH	Time to failure (min)	Comments
2336	Goodyear polyurethane MS clear 10-1 cm	Epoxy	10-12	500	80.0	No Damage
2337	Goodyear polyurethane MS clear 10-1 cm	Epoxy	10-12		70.0	Erosion of Adhesion?
2338	Goodyear polyurethane MS clear 10-1 cm	Epoxy	10-12		70.0	No Damage
2339	Goodyear polyurethane MS clear 10-1 cm	Epoxy	10-12		180.0	No Damage
2340	Goodyear Polyurethane MS clear 10-1 cm	Epoxy	10-12		180.0	No Damage
2341	Desoto Flex white 5 mil over Rm115 (white 3.5 mils)	Aluminum	8.5		33.4	Erosion Failure
2342	Desoto Flex white 5 mil over RM115 (white 3.5 mils)	Aluminum	8.5		33.4	Erosion Failure
2343	Desoto Flex white 5 mil over RM115 (white 3.5 mils)	Aluminum	8.5		32.5	Erosion Failure
2344	Desoto Flex white 5 mil over RM115 (white 3.5 mils)	Aluminum	8.5	500	32.5	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
2345	Desoto Flex white 5 mil over RM115 (white 3.5 mils)	Aluminum	8.5	500	34.0	Erosion Failure
2346	Desoto Flex white 5 mil over RM115 (white 3.5 mil)	Aluminum	8.5		34.0	Erosion Failure
2347	Desoto Flex white (3 mils over	Aluminum	8		36.4	Erosion Failure
2348	Olin low pig. white 5 mils	Aluminum	8		36.4	Erosion Failure
2349	Olin low pig. white 5 mils	Aluminum	8		39.1	Erosion Failure
2350	Olin low pig. white 5 mils.	Aluminum	8		39.1	Erosion Failure
2351	Olin low Pig. white 5 mils	Aluminum	8		29.7	Erosion Failure
2352	Olin low pig. white 5 mils	Aluminum	8		29.7	Erosion Failure
2361	Polyphenylene sulfide with TiO_2	Epoxy	8		5.8	Erosion Failure
2362	Polyphenylene sulfide with TiO_2	Epoxy	8		5.8	Erosion Failure
2362	PPS + TiO_2+ Teflon	Epoxy	8	500	5.5	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
2363	PPS + TiO_2+ Teflon	Epoxy	8	500	5.5	Erosion Failure
2364	PPS + TiO_2 (Poor hiding Thin)	Epoxy	8		5.5	Surface Pitting
2373	White urethane (Hughson A276 over CD1154)	Epoxy	50		44.2	Erosion Failure
2374	White urethane (Hughson A276 over CD1154)	Epoxy	50		44.2	Erosion Failure
2375	White urethane (Hughson A276 over CD-1154)	Epoxy	50		10.0	Erosion Failure
2376	White urethane (Hughson A276 over CD1154)	Epoxy	50		10.0	Erosion Failure
2377	White urethane (Hughson A276 over CD1154)	Epoxy	50		49.9	Severe Surface Damage
2378	White urethane (Hughson A276 over CD1154)	Epoxy	50		49.9	Erosion Failure
2379	White urethane (Hughson A276 over CD1154)	Aluminum	67		10.7	Erosion Failure
2380	White urethane (Hughson A276 over CD1154)	Aluminum	67	500	10.7	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
2381	White urethane (Hughson A276 over CD1154)	Aluminum	67	500	46.6	Severe Surface Damage
2382	White urethane (Hughson A276 over CD1154)	Aluminum	67		46.6	Erosion Failure
2383	White urethane (Hughson A276 over CD1154)	Aluminum	67		54.6	Severe Damage
2384	White urethane (Hughson A276 over CD1154)	Aluminum	67		54.6	Severe Damage
2385	Aliphatic white A276	Epoxy	32		7.5	Erosion Failure
2386	Aliphatic white A276	Epoxy	32		7.5	Erosion Failure
2387	Aliphatic white A276	Epoxy	32		10.8	Erosion Failure
2388	Aliphatic white A276	Epoxy	32		10.8	Erosion Failure
2389	Aliphatic white A276	Epoxy	32		10.5	Erosion Failure
2390	Aliphatic white A276	Epoxy	32		10.5	Erosion Failure
2585	PACE-White urethane	Aluminum	10-11	500	27.0	No Damage

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
2586	PACE - White Urethane	Aluminum	10-11	500	27.0	Erosion Failure
2587	PACE - White Urethane	Epoxy	10-11		4.4	Erosion Failure? ?
2588	PACE - White Urethane	Epoxy	10-11		4.4	No Damage
2589	PACE - Gray Urethane	Aluminum	10-11		20.3	Erosion Failure
2590	PACE - Gray Urethane	Aluminum	10-11		20.3	Erosion Failure
2591	PACE - Gray Urethane	Epoxy	10-11		6.9	Erosion Failure
2592	PACE - Gray Urethane	Epoxy	10-11		6.9	Erosion Failure
2643	Nordel 1070 EPDM	Epoxy	30		35.1	Erosion Failure
2644	Nordel 1070 EPDM	Epoxy	30		35.1	Erosion Failure
2645	Nordel 1070 EPDM	Epoxy	30		39.3	Erosion Failure
2646	Nordel 1070 EPDM	Epoxy	30		39.3	Erosion Failure
2647	Nordel 1070 EPDM Heat Aged	Epoxy	30	500	38.7	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
2648	Nordel 1070 EPDM Heat Aged	Epoxy	30	500	38.7	Slight Pitting
2649	Nordel 1070 EPDM Heat Aged	Epoxy	30	↑	41.7	Erosion Failure
2650	Nordel 1070 EPDM Heat Aged	Epoxy	30		41.7	Erosion Failure
2655	Nordel 1070 Black EPDM	Epoxy	20		1.5	Adhesion Loss
2656	Nordel 1070 Black EPDM	Epoxy	20		1.5	No Damage
2657	Nordel 1070 EPDM unfilled	Epoxy	20		9.3	Adhesion Loss
2658	Nordel 1070 EPDM unfilled	Epoxy	20		9.3	Adhesion Loss
2659	Hydrin 200 unfilled	Epoxy	20		28.2	Surface Damage
2660	Hydrin 200 unfilled	Epoxy	20		28.2	Surface Damage w/ 3 or 4 pits
2661	Silphenyl-Dimethyl siloxane	Epoxy	12-15		24.5	Erosion Failure
2662	Silphenyl-Dimethyl siloxane	Epoxy	12-15		23.7	Erosion Failure
2663	Silphenyl-Dimethyl siloxane	Epoxy	12-15	↓	13.8	Erosion Failure
2664	Interlock quartz	Epoxy Resin	-	500	10.0	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
2665	Interlock quartz	Epoxy Resin	-	500	10.0	Erosion Failure
2680	EPDM -R-35	Epoxy	30		55.4	Erosion Failure
2681	EPDM -5CS4419	Epoxy	30		55.4	Erosion Failure
2682	EPDM -R-35	Epoxy	30		60.2	Erosion Failure
2683	EPDM -R-35	Epoxy	40		60.2	Erosion Failure
2684	EPDM -5CS4419	Epoxy	40		51.9	Erosion Failure
2685	EPDM -5CS4419	Epoxy	40		51.9	Erosion Failure
2686	EPDM white R-35	Epoxy	32		50.1	Severe surface damage
2687	EPDM white 5CS4419	Epoxy	32		50.1	Erosion Failure
2688	Hydrin R-35	Epoxy	34		70.2	Surface Erosion
2689	Hydrin 5CS4419	Epoxy	35		70.2	Surface Erosion-Adhesion
2834	Sterling Gary ureth	Epoxy	12		1.8	Erosion Failure
2835	Sterling Gary ureth	Epoxy	12		1.8	Erosion Failure
2836	Sterling Gary ureth	Epoxy	12		1.9	Erosion Failure
2837	Sterling Gary ureth	Epoxy	12		1.9	Erosion Failure
2838	Sterling Gray ureth	Epoxy	12		1.8	Erosion Failure
2839	Sterling Gray ureth	Epoxy	12		1.8	Erosion Failure
2840	Sterling Gray ureth	Epoxy	12		1.8	Erosion Failure
2841	Sterling Gray ureth	Epoxy	12		1.8	Erosion Failure
2842	U.S. Polymeric ureth	Epoxy	12		0.3	Erosion Failure
2843	U.S. Polymeric ureth	Epoxy	12	500	0.3	Erosion Failure

TABLE VIII (CONT'D)

RAIN EROSION DATA 1 INCH/HOUR SIMULATED RAINFALL

AFML No.	Coating	Substrate	Coating Thickness (mils)	Velocity MPH	Time to failure (min)	Comments
2844	U.S. Polymeric ureth	Epoxy	12	500	0.2	Erosion Failure
2845	U.S. Polymeric ureth	Epoxy	12		0.2	Erosion Failure
2846	White Astrocoat Rml15W	Epoxy	12		41.5	Erosion Failure
2847	White Astrocoat Rml15W	Epoxy	12		41.5	Erosion Failure
2848	White Astrocoat Heat Aged	Epoxy	12		92.7	Erosion Failure
2849	White Astrocoat Heat Aged	Epoxy	12		92.7	Erosion Failure
2878	BPI 373 low void Polyimide	Glass laminate	-		10.0	Erosion Damage
2879	BPI 383 low void Poluimide	Glass laminate	-		10.0	Erosion Damage
2902	3-D angle interlock quartz	Epoxy	-		10.0	No Failure
2965	Dow Corning Silicone	Epoxy	15		0.4	Erosion Failure
2966	Dow Corning Silicone	Epoxy	15		0.4	Erosion Failure
2967	Dow Corning Silicone	Epoxy	15		0.7	Erosion Failure
2968	Dow Corning Silicone Doublecoated	Epoxy	15	500	0.7	Erosion Failure

* Typical Values for MIL-C-83231 Polyurethane Coatings on Glass Epoxy.

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13. ABSTRACT

Subsonic investigations of polymeric coatings, bulk polymers, and fiber reinforced polymeric composites for their erosion behavior and the influence of materials variables on their erosion response are described.

Polymeric coatings such as epoxies, polyesters, and amide-imides are brittle relative to the impinging water droplets with rupture of the film occuring very rapidly The most resistant coatings such as elastomeric polyurethanes typically show no surface erosion at all but fail at isolated points associated with a breakdown of the composite (i. e., glass-epoxy) underneath the coating. Other elastomeric coatings such as neoprene will gradually erode on the surface by structural failure or tearing within the film; erosion of the composite then follows. The elastomeric coatings protect the surface by pulse attenuation of the impact load and by protecting the composite from the radial outflow of the impinging drop. The modulus of these coatings is related to their performance in a rain environment since it governs the stress level which is transmitted to the substrate.

The void content and type of reinforcement are shown to significantly influence the behavior of fiber reinforced composite structures in a subsonic rain erosion environment whether uncoated or coated. The effects of various fiber lay-up schemes with a particular fiber reinforcement have been found to be minor compared to void content effects.

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Form 1473 Abstract (Continued)

The addition of reinforcement to thermoplastic resin matrices increases the erosion rates of these materials by breakage of fibers and resulting loss of material. In thermosetting resins, the addition of reinforcement reduces the erosion rate of a bulk material by limiting the chunking and breakout of large pieces.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Rain Erosion Materials Parameters Polymeric Coatings Polymeric Composites Subsonic Velocity						

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